NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1019

RELATION BETWEEN INFLAMMABLES AND IGNITION SOURCES IN AIRCRAFT ENVIRONMENTS

By WILFRED E. SCULL

1951

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight$=mg$

g Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass$=\frac{W}{g}$

I Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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By WILFRED E. SCULL

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Cleveland, Ohio

National Advisory Committee for Aeronautics

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REPORT 1019

RELATION BETWEEN INFLAMMABLES AND IGNITION SOURCES IN AIRCRAFT ENVIRONMENTS[1]

By Wilfred E. Scull

SUMMARY

A literature survey was conducted to determine the relation between aircraft ignition sources and inflammables. Available literature applicable to the problem of aircraft fire hazards is analyzed and discussed herein. Data pertaining to the effect of many variables on ignition temperatures, minimum ignition pressures, minimum spark-ignition energies of inflammables, quenching distances of electrode configurations, and size of openings through which flame will not propagate are presented and discussed. Ignition temperatures and limits of inflammability of gasoline in air in different test environments, and the minimum ignition pressures and minimum size of openings for flame propagation in gasoline-air mixtures are included; inerting of gasoline-air mixtures is discussed.

The results of the survey indicate the possibility of reducing aircraft-fire hazards by:

(1) Preventing contact of fuels or fuel vapors with the hot exhaust surfaces

(2) Releasing an extinguishing agent inside of and around the exhaust system if a crash is imminent

(3) Reducing the temperature of the exhaust duct or gases below the surface-ignition temperatures of gasoline and lubricating oil in the event of a crash

(4) Increasing the surface-ignition temperatures of gasoline and lubricating oil

(5) Using fuels of reduced volatility

(6) Eliminating the electrical generating system as an ignition hazard in the event of a crash

(7) Inerting the engine nacelles and wing compartments.

INTRODUCTION

As a part of the aircraft-fire-research program, a literature survey was conducted at the NACA Lewis laboratory during 1949–50 to determine the relation between inflammables and ignition sources. An effort has been made to correlate the limited data available with the problem of fire hazards in aircraft environments. The results of the survey are presented in three parts corresponding to the main sources of ignition in aircraft environments; that is, heated surfaces, electric sparks and arcs, and flames or hot gases.

The following variables have been considered in the ignition of fuels or fuel vapors by the different ignition sources:

Heated surfaces	Electric sparks and arcs	Flames or hot gases
Ignition temperature	Type of spark	Mixture composition
Mixture composition	Minimum spark-ignition energy	Mixture exposure duration
Ignition lag	Mixture composition	Limiting size of openings for flame propagation
Mixture velocity	Electrode spacing	Size, shape, and material of openings for flame propagation
Mixture turbulence	Electrode material and configuration	Mixture pressure
Condition and composition of the ignition surface	Spark potential	Mixture temperature
Ignition surface area	Spark duration	Effect of diluents
Fuel composition	Mixture velocity	
Mixture pressure	Mixture pressure	
Effect of diluents	Mixture temperature	
	Effect of diluents	

Although quantitative agreement among the large quantities of data in the literature is not to be expected because of the many different experimental techniques used, it is believed that comparison of the effects of the different variables as compiled herein will provide valuable information toward reducing aircraft-fire hazards.

I—IGNITION BY HEATED SURFACES

Although the data pertaining to the ignition of inflammable mixtures by heated surfaces are quite extensive, little agreement exists in technique, terminology, or results of various investigators. In the following discussions, an effort has been made to allow for different experimental techniques and to use a system of nomenclature presently acceptable in the combustion field.

TERMINOLOGY

IGNITION TEMPERATURES

The ignition temperature of an inflammable mixture is the minimum temperature to which the mixture must be raised in order that the rate of heat loss from the mixture is more than balanced by the rate at which heat is evolved from the mixture by exothermic chemical reaction. At this temperature, the reaction becomes self-accelerating and the temperature increases until self-propagating inflammation of the mixture occurs. A definite lag during which the reaction is self-accelerating thus exists, the magnitude of which is determined by the rapidity of acceleration of the reaction velocity. Defined in this manner, the ignition temperature of an inflammable is a mixture temperature and does not necessarily correspond to and may be considerably lower than the inflammation temperature or mixture temperature at the instantaneous appearance of flame. The ignition temperature of an inflammable, therefore, cannot be regarded

[1] Supersedes NACA TN 2227, "Relation Between Inflammables and Ignition Sources in Aircraft Environments" by Wilfred E. Scull, 1950.

as a physical constant, but must depend on the experimental conditions under which it is determined. Mixture composition, pressure, and temperature and the presence of catalysts or inhibitors, which accelerate or delay the reaction, are some of the variables affecting the lag before inflammation. The lowest temperature at which any quantity of inflammable will ignite is known as the minimum ignition temperature of the inflammable for the experimental method employed.

Efforts of various investigators to determine the ignition temperatures of inflammables have resulted in different methods of attaining the mixture temperature at which self-accelerating reaction begins. As a result of these experimental methods and the difficulties of determining the defined ignition temperature, many of the ignition temperatures reported in the literature are the temperatures of heated elements, which raise the mixture temperature to a level of self-accelerating reaction. These heated element temperatures are not necessarily the same as the ignition temperature of the mixture. In general, the temperatures reported hereinafter are specifically designated as to the temperature actually measured.

The most important methods employed to determine the ignition temperatures are as follows:

(1) Crucible methods—static and dynamic
(2) Dynamic heated-tube method
(3) Adiabatic-compression method
(4) Bomb method.

In all these methods, various criterions have been chosen as indications of ignition and inflammation. A sudden rapid pressure rise, an increase in temperature, or both, have been used as indications of ignition, whereas the appearance of flame or explosive sounds have been taken to indicate mixture inflammation.

The crucible methods (static or dynamic, depending on whether the supporting atmosphere in the crucible is quiescent or flowing) appear to be the most popular methods of determining the ignition temperatures of liquid inflammables. Also known as the oil-drop methods, the crucible methods are variations of a method described in references 1 and 2. Essentially, the method consists in dropping a drop of the inflammable liquid through an opening into a crucible fitted into a heated iron or steel block containing either quiescent or flowing air or oxygen. The crucible temperature and ignition lag are measured when the droplet bursts into flame. A precise knowledge of the exact mixture composition at the instant of ignition is unobtainable. Furthermore, the latent heat of vaporization of the droplet must be supplied by the system. In these methods, experimentally measured ignition temperatures are the temperatures of the heated crucible surfaces causing ignition.

The dynamic heated-tube method, which attempts to nullify the effect of enclosing surfaces, is described in reference 3. In this method, the flowing inflammable vapor and the supporting atmosphere are separately heated in concentric quartz or pyrex tubes. The inflammable vapor is metered into the supporting atmosphere in the large tube through a small orifice in the end of the small tube. In this case, the experimentally measured ignition temperature is the mixture temperature at which inflammation occurs after a measured time lag. Such a method permits easy variation of the inflammable over-all mixture composition.

A description of the adiabatic-compression method of determining ignition temperatures is given in reference 4. In this method, the inflammable mixture of vapor and air or vapor and oxygen is suddenly compressed. Ignition occurs after a lag depending on the temperature reached by the compression process. The ignition temperature is computed from the experimentally measured compression ratio. This method is advantageous in that the mixture composition is known, accurate ignition-lag measurements are possible, and the relatively cold walls of the compression cylinder preclude any catalytic influence. Disadvantages of such a method are the large cooling losses, the difficulty of determining the exact value of the compression exponent γ, and the fact that the experimentally determined ignition temperature pertains to the compression pressure.

The bomb or heated-chamber method of determining ignition temperatures is described in reference 5. Essentially, the method consists in introducing an inflammable mixture into an evacuated chamber heated to a known temperature. The experimentally measured ignition temperature is taken as the chamber temperature that causes ignition after a measured ignition lag. Disadvantages of the method are the possible catalytic effects of the chamber surface and the heat required to increase the mixture temperature to the chamber temperature. Advantages of the method are the knowledge of the mixture composition and the ease with which normal-length ignition lags can be measured. Very small ignition lags are difficult to measure because of the time interval required to admit the mixture to the chamber.

The results of all these methods are affected by the experimental conditions and characteristics of the inflammables investigated. Some of the factors significantly affecting the experimentally determined ignition temperatures of inflammable substances are:

(1) Fuel composition
(2) Fuel-air or fuel-oxygen ratio
(3) State of inflammable—vapor or liquid
(4) Size of inflammable drop
(5) Mixture pressure and temperature
(6) Relative stagnation of mixture—turbulent or quiescent
(7) Thermal conductivity of mixture
(8) Ignition-lag period
(9) Surface composition and physical character of ignition element
(10) Surface area of ignition element
(11) Surface-volume ratio of ignition chamber
(12) Ignition-element temperature
(13) Approach to ignition temperature—from mixture temperatures above or below ignition temperature
(14) Method of introduction of inflammable to ignition element.

As a result of the effects of these variables on ignition temperature, the experimentally determined ignition temperature of an inflammable may be different in various sources of information. Data from the same source, however, show the trends and the relative effects of different variables.

LIMITS OF INFLAMMABILITY

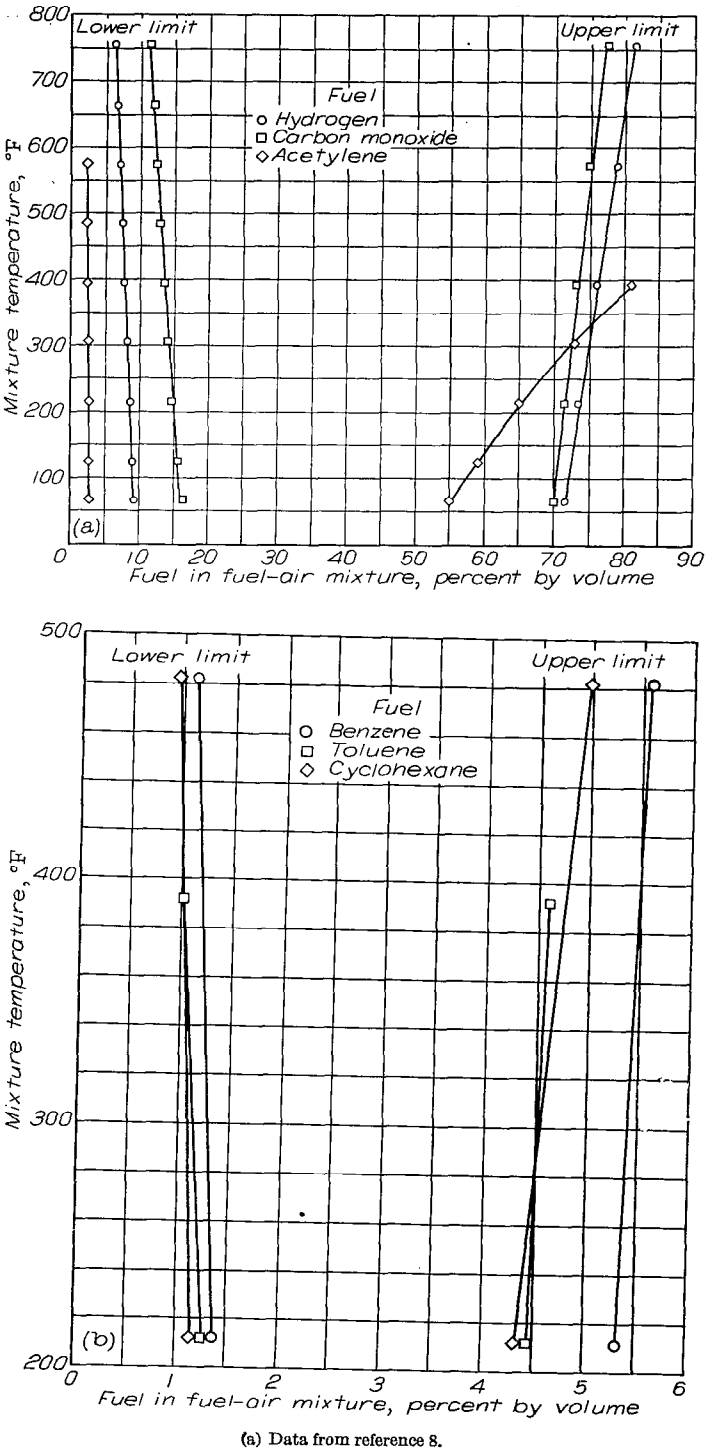
The limits of inflammability of a mixture, also known as the inflammation or explosive limits, are those proportions, generally volumetric, of fuel in air or oxygen that are just capable of self-propagation of flame throughout the entire mixture once inflammation has been initiated in a portion of the mixture. These limits are generally determined for upward, continuous self-propagation of a flame in a vertical tube of sufficient diameter such that the wall cooling effects are negligible. Mixtures just below the lower limits or just above the upper limits of inflammability may burn around the ignition source, but are incapable of propagating flame throughout the entire mixtures. In addition, the mixture volume must be large enough that the flame may still propagate even after the energy input required for the initial inflammation has been dissipated. For any particular inflammable, the limits of inflammability are affected by the direction of flame propagation, type of test apparatus, the amount of water vapor present in the mixture, and the mixture pressure and temperature.

Flame progress may be assisted or retarded by convection depending on whether the flame propagation is in an upward, horizontal, or downward direction; therefore a statement of the method of observation of the limits of inflammability is necessary. Generally, wider limits are found for upward than for downward flame propagation at atmospheric pressure and temperature. Data from reference 6 indicate that the lower and upper limits of inflammability of methane in air at atmospheric conditions, as determined for upward flame propagation, are increased and decreased, respectively, approximately 10 percent for downward flame propagation. Values reported herein are for upward flame propagation unless specified otherwise.

The effect of the type of test apparatus and the method of ignition used in the determination of the inflammability limits of various mixtures are minor. The inflammability range of several mixtures increased with increasing tube diameter up to a tube diameter of 2 inches, because of the decreased cooling effect of the walls. At atmospheric pressure, tube diameters greater than 2 inches have very little effect on the limits. In addition, literature indicates (reference 7) that inflammability limits are unaffected by the method of ignition—spark, flame, or fusion of a platinum wire.

The lower limit of inflammability of a mixture is only slightly affected by the amount of water vapor present in the normal atmosphere. Water-vapor presence reduces the upper limit because of displacement of oxygen by the water vapor. Because the amount of oxygen is important in an upper-limit mixture, the amount of inflammable capable of being ignited decreases with the decreased oxygen content, resulting in an over-all reduction of the upper inflammability limit.

The effect of varying mixture temperature on the downward propagation limits of inflammability of several mixtures is expressed in figure 1. The upper and lower limits of inflammability of the various mixtures decrease and increase, respectively, approximately linearly with decreasing mixture temperatures.



(a) Data from reference 8.

(b) Data from references 9 and 10.

FIGURE 1.—Effect of mixture temperature on downward propagation limits of inflammability of combustible fuel-air mixtures at atmospheric pressure.

EXPERIMENTAL RESULTS IN PUBLISHED LITERATURE

Knowledge of the approximate temperature of heated surfaces capable of causing ignition is desirable because ignition of fire in aircraft may be caused by the exposure of inflammables to heated surfaces. Published experimental results for heated-surface ignition indicate the effects of a number of different variable experimental conditions. As far as possible, the results presented here are accompanied by data specifying the experimental conditions.

EFFECT OF MIXTURE COMPOSITION

Ignition temperatures.—The relative effect of mixture composition on the surface ignition temperatures of quiescent natural-gas–air mixtures ignited by single electrically heated nickel strips is shown in figure 2. The nickel strips of varying widths were mounted in the center of a chamber of 4½-cubic-foot capacity. The surface temperatures of the heated strips were measured by peened-in thermocouples. For the various widths of the heated ignition surfaces, the surface ignition temperature of the mixture increases approximately linearly with increasing proportions of natural gas in the mixture between the limits of inflammability. A few comparative experiments with methane in place of natural gas indicated that these mixtures ignited at approximately 30° F greater surface ignition temperatures than the natural-gas–air mixtures. Other investigations (reference 5, for example) indicated that the ignition temperatures of methane-air and natural-gas–air mixtures are lower than those of figure 2. This discrepancy is explained in reference 11 by the fact that the temperature of a heated ignition surface is greater than the true ignition temperature of the mixture. Although the ignition temperatures of methane-air and natural-gas–air mixtures increase with increasing proportions of fuel; the ignition temperatures decrease with increasing proportions of fuel for the higher hydrocarbons of the paraffin series. The

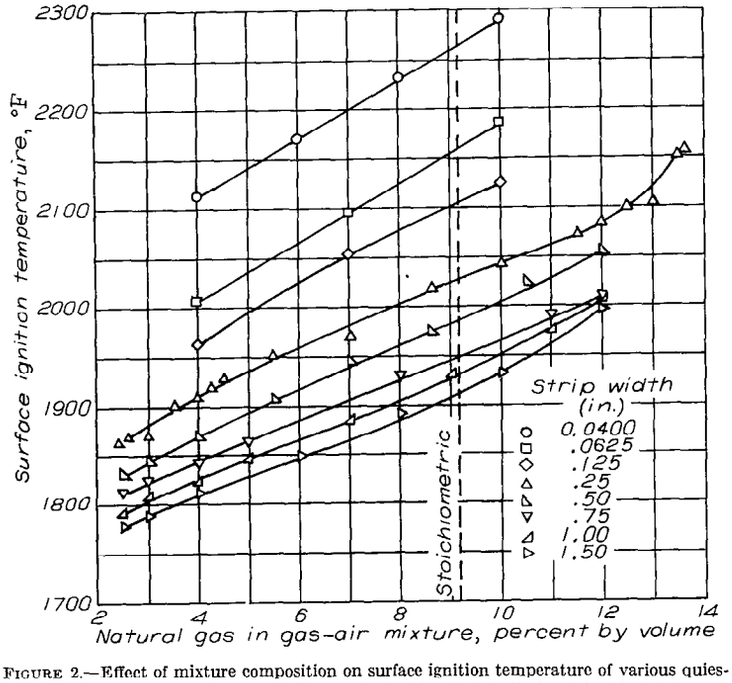


FIGURE 2.—Effect of mixture composition on surface ignition temperature of various quiescent natural-gas—air mixtures. Mixtures ignited by electrically heated nickel strips cut from same sheet of No. 18 B and S gage commercial nickel; length of strips, 4¼ inches. (Data from reference 11.)

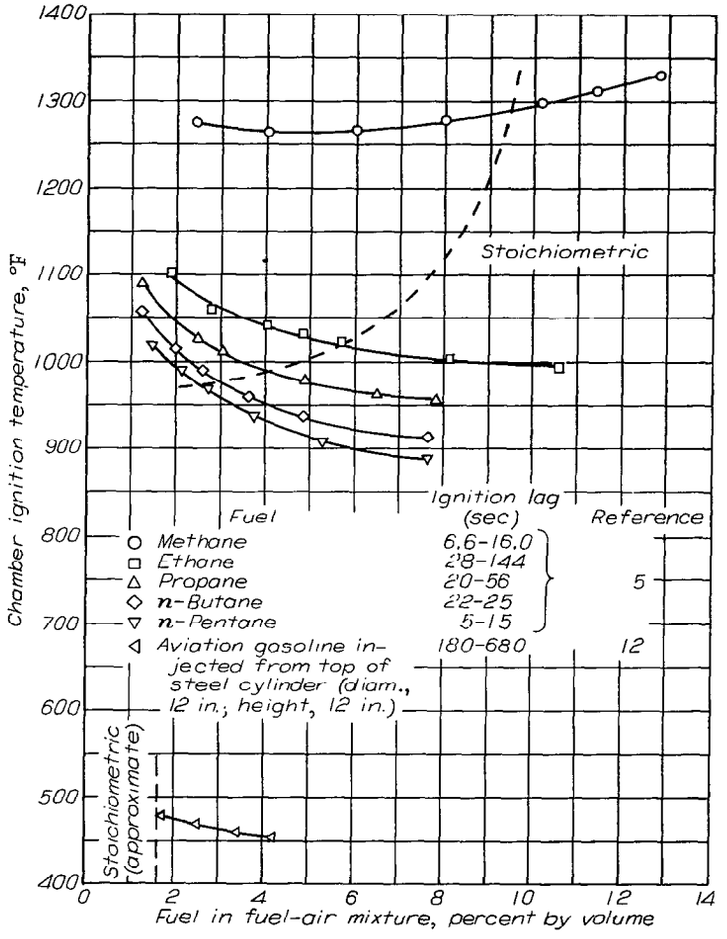


FIGURE 3.—Effect of mixture composition on chamber ignition temperatures of various fuels at atmospheric pressure as determined by bomb ignition method except as shown.

chamber ignition temperatures of mixtures of the higher paraffin hydrocarbons and air decrease with increasing proportions of fuel within the range investigated (fig. 3). It might be expected from figure 3 that the ignition temperatures of mixtures of hydrocarbons and air might again increase with increasing richness of the mixtures. Although data from references 13 to 15 are erratic, it has been concluded by the authors that the ignition temperatures of individual mixtures of coal gas, benzene, toluene, methyl alcohol, S–1 fuel, and air, which are approximately constant over a wide range of fuel-air ratios, do increase eventually with increasing richness of the mixtures.

The ignition temperatures of gasoline mixtures, like the ignition temperatures of the higher paraffin hydrocarbons, decrease with increasing proportions of fuel within the range of data available (figs. 4 and 5). The effect of the proportions of fuel, oxygen, and nitrogen on the ignition temperatures of gasoline mixtures as determined by the dynamic heated-tube method is shown in these figures. Similar results are given in reference 13. Without exception, various fuels investigated singly in an engine at two engine speeds and with hot-spot ignition showed sharp increases in the ignition temperatures of lean mixtures.

Zones of ignition and nonignition.—Two types of ignition may exist for the same fuel for certain oxygen-fuel ratios: (1) A low-temperature ignition practically independent of fuel concentration or oxygen-fuel ratio; and (2) a high-

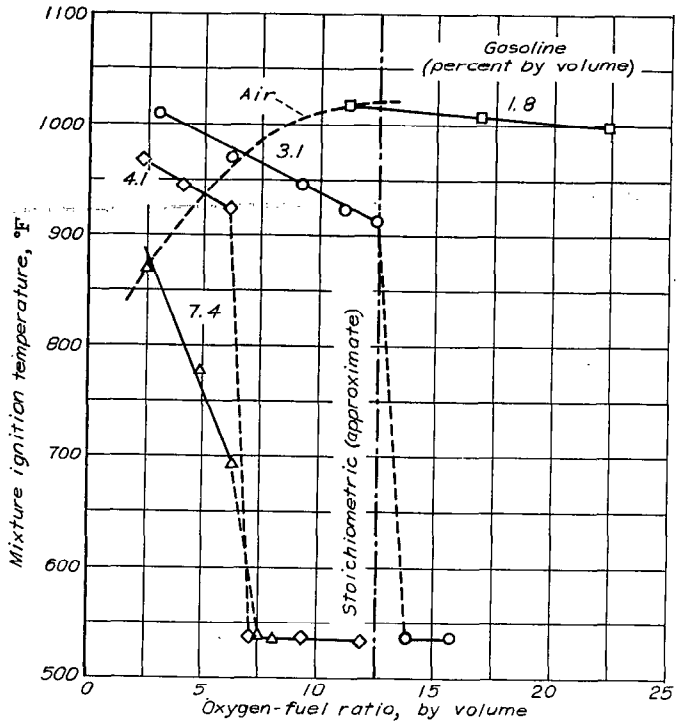


FIGURE 4.—Variation of mixture ignition temperature of gasoline with oxygen-fuel ratio for constant proportions of fuel. Method of ignition, dynamic heated tube; diluent component, nitrogen; supporting atmosphere flow, 230 cubic centimeters per minute at atmospheric pressure and temperature. (Data from reference 16.)

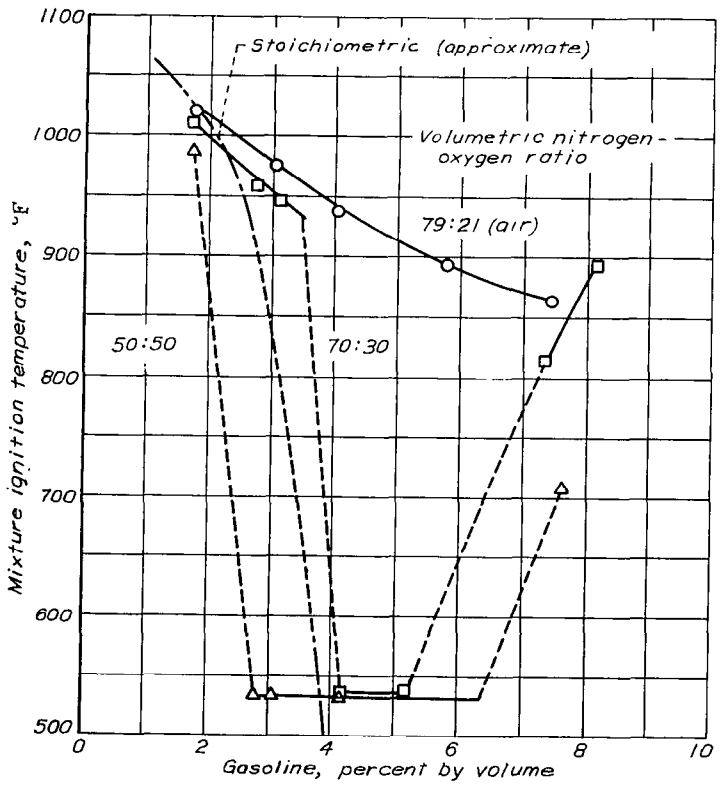
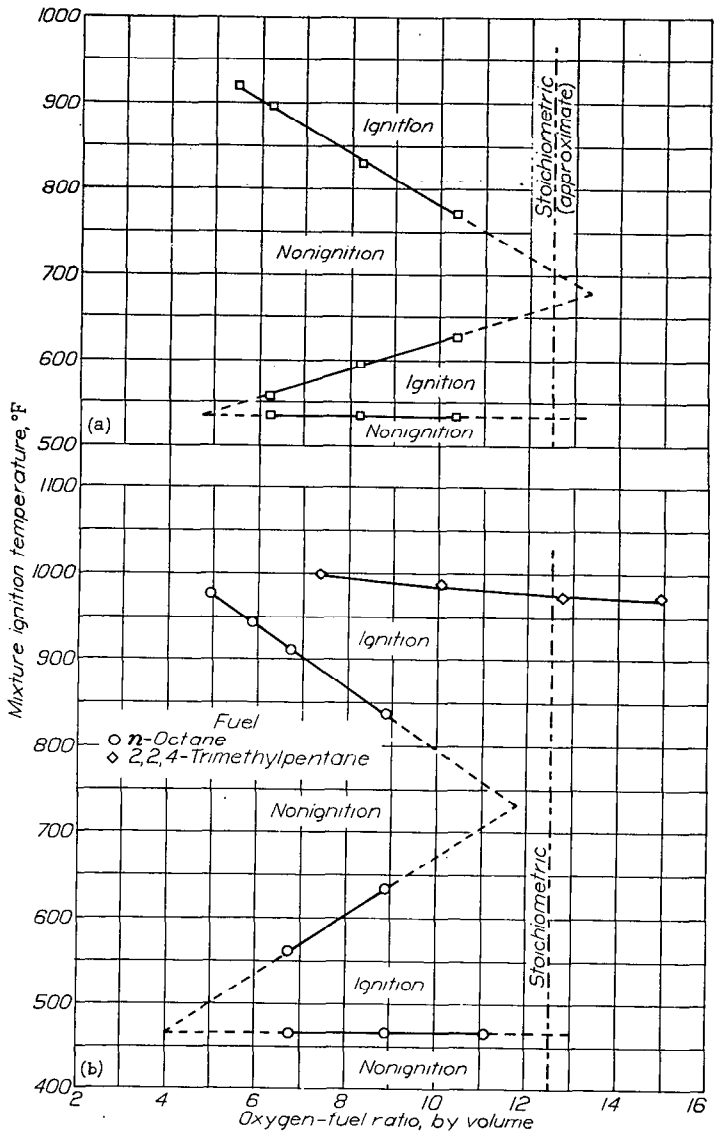


FIGURE 5.—Variation of mixture ignition temperature of gasoline with various proportions of fuel for constant nitrogen-oxygen ratios. Method of ignition, dynamic heated tube; supporting atmosphere flow, 230 cubic centimeters per minute at atmospheric pressure and temperature. (Data from reference 16.)

temperature ignition varying markedly with these variables. The two types of ignition for gasoline-oxygen-nitrogen mixtures are indicated in figures 4 and 5. The ignition temperature of gasoline in air corresponds to the high-temperature



(a) Fuel, gasoline, 4.6 percent by volume.

(b) Fuels, 2,2,4-trimethylpentane, 3.8 percent by volume and n-octane, 4.3 percent by volume.

FIGURE 6.—Ignition characteristics of mixtures of fuel, oxygen, and nitrogen. Method of ignition, dynamic heated tube; supporting atmosphere flow, 230 cubic centimeters per minute at atmospheric pressure and temperature. (Data from reference 16.)

type of ignition. Dynamic crucible tests reported in reference 17 indicate that readily ignited hydrocarbons, such as cetane, heptane, decane, and decahydronaphthalene exhibit zones of nonignition above the minimum ignition temperatures. Similar results, presented in reference 18, indicate that mixtures of straight-chain paraffins, containing three or more carbon atoms and air exhibit zones of nonignition. Oxidation-resistant hydrocarbons, such as benzene, toluene, and 2,2,4-trimethylpentane exhibit no nonignition zone. Ignition and nonignition zones as determined by the dynamic heated-tube method are shown in figure 6 for mixtures of gasoline, normal octane, and isooctane (2,2,4-trimethylpentane) with oxygen and nitrogen. For a fixed proportion of inflammable, the minimum mixture ignition temperature is independent of the oxygen-fuel ratio. The isooctane-oxygen mixture does not exhibit zones of ignition and nonignition, but the ignition temperature of the mixture decreases slightly with increasing oxygen-fuel ratios.

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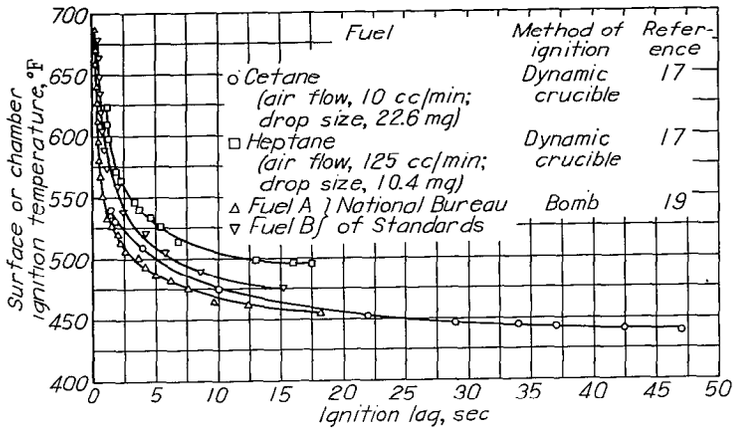


FIGURE 7.—Variation of ignition temperatures of various fuels in air with ignition lag. Cetane and heptane were ignited at atmospheric pressure.

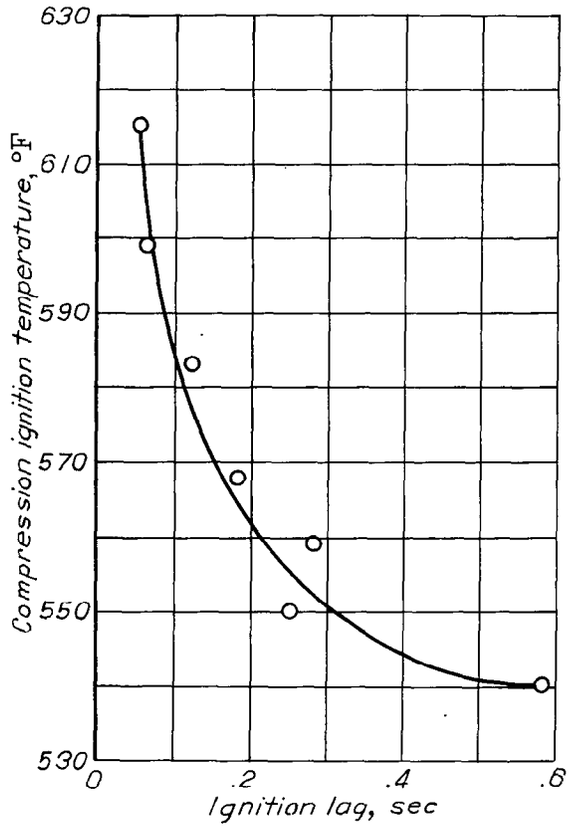


FIGURE 8.—Variation of compression ignition temperature of 1.42 percent by volume mixture of *n*-heptane and air with ignition lag. Method of ignition, adiabatic compression; final pressure, 176 pounds per square inch absolute. (Data from reference 4.)

The phenomenon of zones of nonignition may be due to the occurrence of low-temperature systems capable of cool-flame initiation. Research into the slow combustion of the higher hydrocarbons has shown that slow combustion reactions with accompanying incipient luminescence can be initiated at 300° to 400° F (reference 18). The luminescence increases with increasing temperatures until a cool flame appears. The cool flames move slowly about the reaction chamber, moving more slowly and becoming more diffuse with increasing temperature until they finally disappear leaving behind products of the incomplete combustion strongly aldehydic or peroxidic in character. At still higher

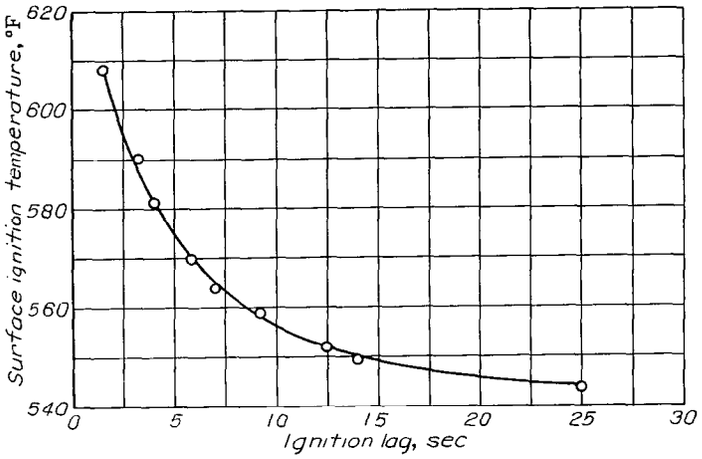


FIGURE 9.—Variation of surface ignition temperature of gasoline in flowing oxygen with ignition lag at atmospheric pressure. Method of ignition, dynamic crucible; ignition surface, platinum. (Data from reference 20.)

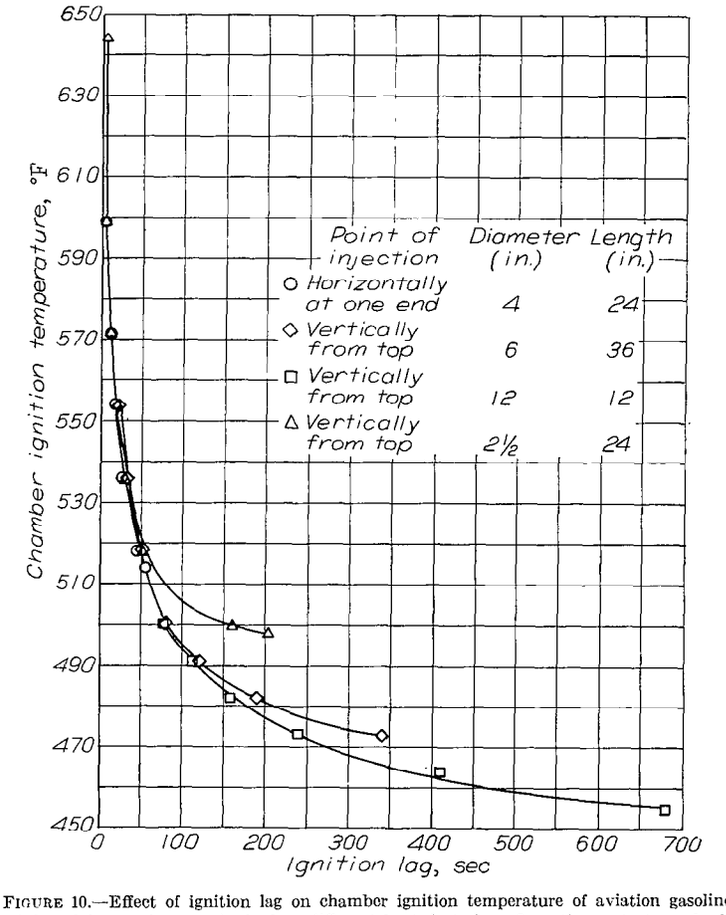


FIGURE 10.—Effect of ignition lag on chamber ignition temperature of aviation gasoline injected into quiescent air, in four different heated steel configurations, at atmospheric pressure. (Data from reference 12.)

temperatures, ignition and complete combustion of the mixture is possible.

EFFECT OF VARYING IGNITION LAG

Ignition lag of quiescent mixtures.—The ignition temperature of inflammable mixtures also depends on the ignition lag or induction period between introduction of the mixture to the ignition source and the first indication of inflammation. The effect of ignition lag on the surface or chamber ignition temperature of various mixtures is expressed in figures 7 to 10. The ignition temperatures of the

inflammable mixtures decrease almost hyperbolically with increasing ignition lags. The minimum ignition temperatures of the mixtures occur when the ignition temperature no longer decreases with increasing time lag. The effect of ignition lag on the ignition temperature of a mixture of *n*-heptane and air as determined by the adiabatic compression method is shown in figure 8. Figure 9 indicates the effect of ignition lag on the surface ignition temperature of gasoline in flowing oxygen as determined using the dynamic crucible method. The ignition temperature of gasoline in flowing oxygen after a 1.5-second lag is approximately 608° F, whereas the minimum ignition temperature, corresponding to a lag of 25 seconds, is approximately 544° F. The influence of ignition lag on the chamber ignition temperature of aviation gasoline injected into four different heated steel configurations is shown in figure 10. The minimum ignition temperature of aviation gasoline as determined from these data is approximately 455° F.

Data, from reference 21, which illustrate the effect of ignition lag on the ignition temperature of aviation gasoline ignited by the heated chamber method when the fuel (4.2 percent by volume in air) was injected from the top into a vertical steel cylinder 12 inches in diameter and 12 inches in height, are given in the following table:

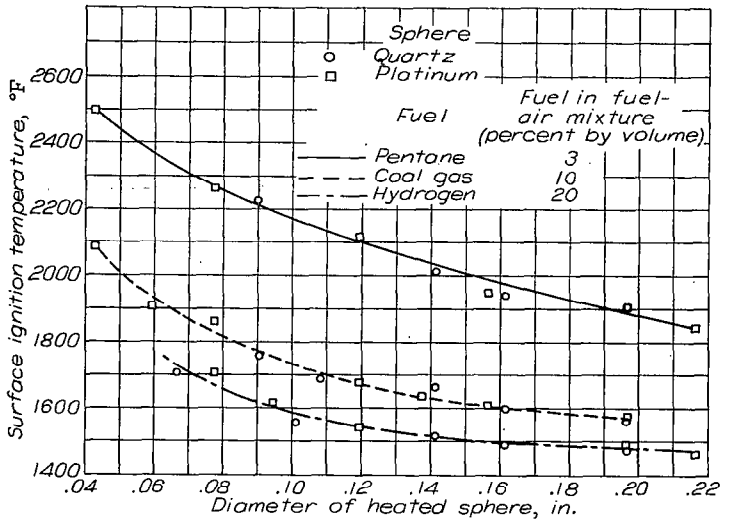
Ignition lag (sec)	Chamber ignition temperature (° F)
7	600
12	570
672	450

Ignition lag of mixtures ignited by heated spheres and rods.—Ignition of inflammable mixtures has also been effected by means of heated spheres shot into the mixture. The effect of the diameter of the heated sphere on the surface ignition temperatures of three fuel-air mixtures ignited by heated quartz and platinum spheres shot into the mixtures at an average velocity of 13.1 feet per second is shown in figure 11 (a). Ignition temperatures of the mixtures decreased with increasing sphere diameter because of the greater ignition area. The criterion for ignition used in reference 22 is the requirement that the initial rate of heat production by the reaction should be greater than the heat loss by conduction. Using this criterion the investigator concludes that the following is theoretically true for each initial sphere velocity:

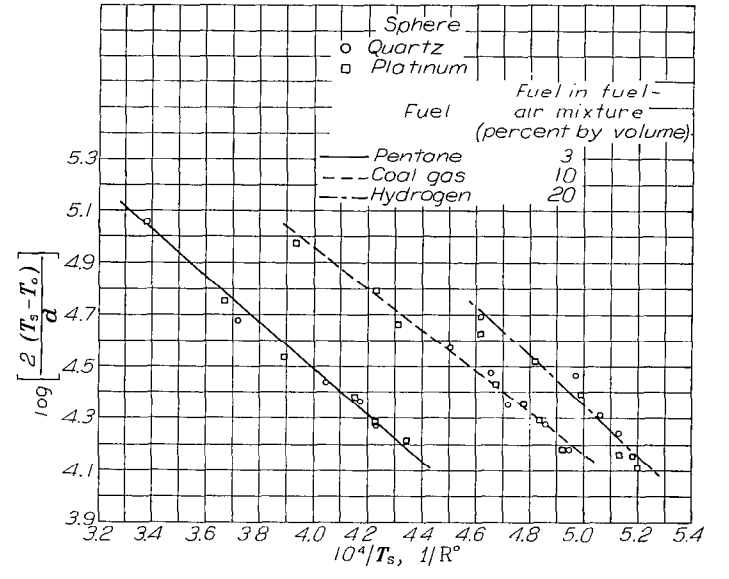
$$\frac{2(T_s-T_o)}{d}=Ke^{-\frac{A}{RT_s}} \qquad (1)$$

where

A apparent energy of activation of mixture
d diameter of sphere
K constant characterizing gas mixture and sphere material
R gas constant
T_o mixture temperature
T_s heated sphere temperature



(a) Experimental data.



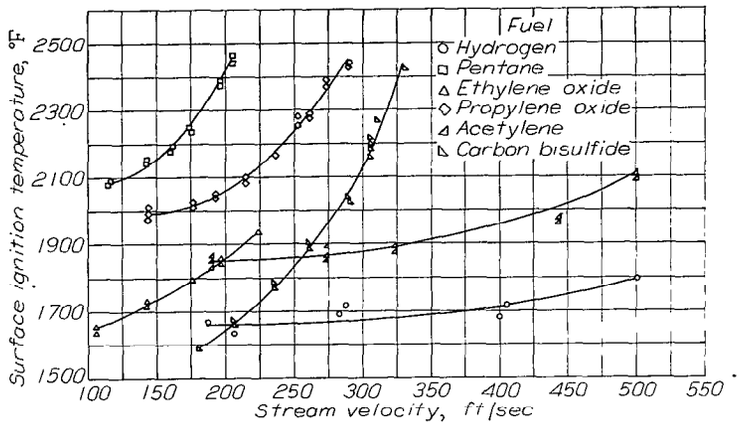
(b) Reduced data.

FIGURE 11.—Effect of sphere diameter on surface ignition temperature of three fuel-air mixtures, at atmospheric pressure, ignited by heated quartz and platinum spheres shot into mixture at average velocity of 13.1 feet per second. (Data from reference 22.)

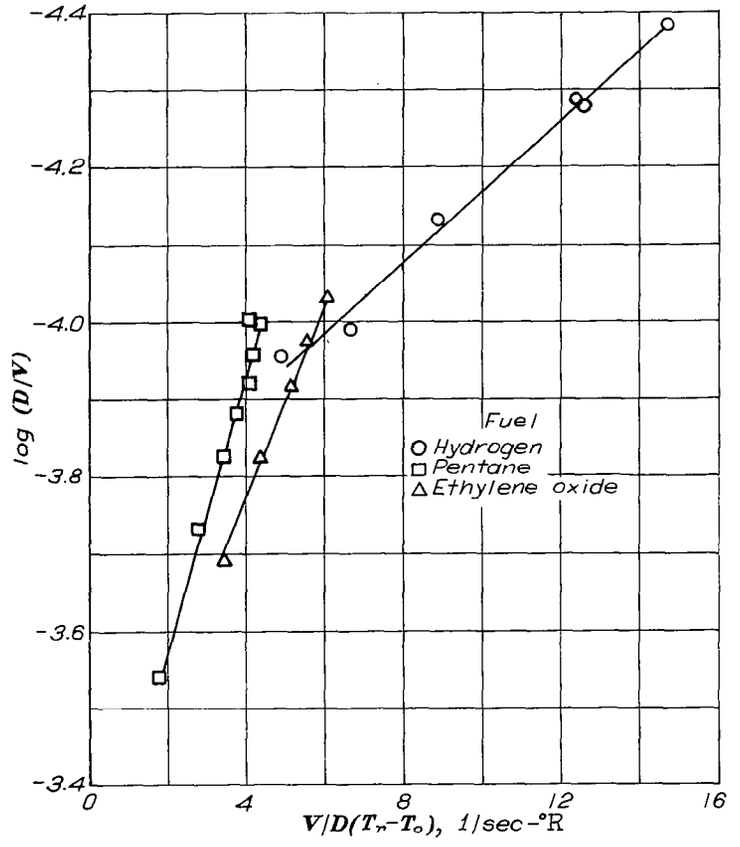
The data of figure 11 (a) have been replotted in figure 11 (b).

The same relative effect of velocity on the ignition temperatures of various inflammable mixtures is indicated in figure 12. The ignition source is at rest in this case and the mixture is in motion. The ignition temperature of the flowing mixture is the temperature of a rod situated in the center of a duct filled with flowing mixture and heated sufficiently to cause ignition of the mixture. The measured velocity is the velocity at the center of the duct. High mixture velocities correspond to short ignition lags; thus, the ignition temperature of an inflammable mixture increases with increasing velocity of the mixture.

The effect of variation of rod diameter on the ignition temperature of the mixture is expressed in figure 12 (b).



(a) Experimental data.



(b) Reduced data.

FIGURE 12.—Variation of surface ignition temperature of various fuels in air with gas-stream velocity. Ignition by ¼-inch heated stainless-steel rods. Mixtures, stoichiometric at atmospheric pressure and temperature of 155° F. (Data from reference 23.)

For flowing mixtures ignited by heated metal rods, the following equation (reference 23) may be applied:

$$\frac{D}{V}e^{-\frac{E}{RB}\left[\frac{V}{D(T_r-T_o)}\right]}=C \qquad (2)$$

where

B,C constants
D heated-rod diameter
E energy of activation of mixture
R gas constant
T_o flowing mixture temperature
T_r heated-rod temperature
V velocity of mixture flowing past heated rod

In cases of ignition of inflammable mixtures by both heated spheres and heated rods, the ignition effectiveness depends on the temperature of the ignition source, the size of the ignition source, and the duration of contact of the mixture with the ignition source. Factors related to these three criterions of ignition effectiveness are given in equation (2), which pertains to the ignition of flowing gas mixtures by heated metal rods. A factor that pertains to the duration of contact of the mixture with the ignition source is lacking in equation (1), which involves the ignition of quiescent gas mixtures by heated spheres shot into a mixture. This omission appears to be due to the author's criterion of ignition (reference 22) that recognized heat losses only by conduction.

Effect of turbulence.—Literature pertaining to the effect of turbulence on the ignition temperature of inflammable mixtures is not extensive. The available data contain no quantitative measurements of the amount of turbulence. Figure 13, which also includes the data of figure 2, indicates the effect of gentle turbulence excited by a small fan at the top of the ignition chamber on the ignition temperatures of natural-gas–air mixtures. Mild turbulence of a mixture decreases the mixture ignition temperatures. Subsequent investigation (reference 12), however, has contradicted this result. When the turbulence is sufficiently great, the

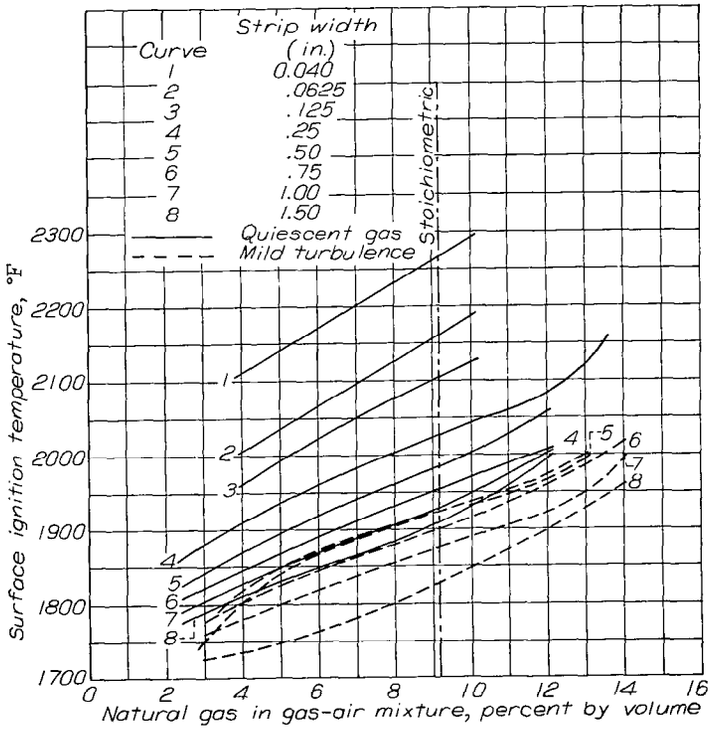


FIGURE 13.—Effect of mild turbulence on surface ignition temperature of various natural-gas–air mixtures. Mixtures ignited by electrically heated nickel strips cut from same sheet of No. 18 B and S gage commercial nickel. Length of strip, 4¼ inches. (Data from reference 11.)

ignition temperatures are increased. According to figure 14, gentle stirring of an aviation-gasoline–air mixture increases the mixture ignition temperature approximately 30° F. Similar data have been found concerning the effect of mild turbulence on the ignition temperatures of stoichiometric mixtures of methane and oxygen, and hydrogen and oxygen.

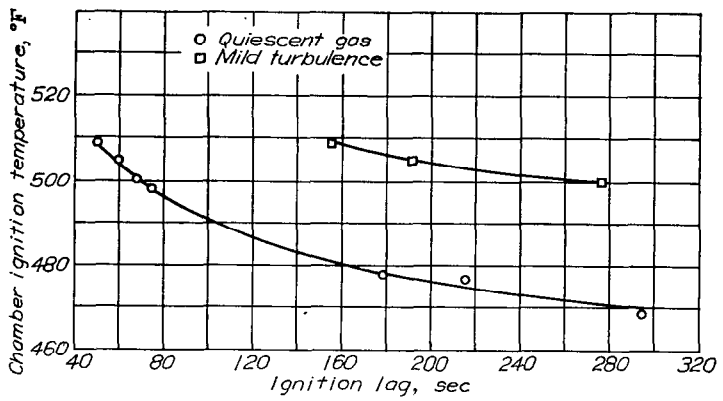


FIGURE 14.—Influence of mild turbulence on chamber ignition temperature of aviation gasoline injected into top of steel cylinder, 6 inches in diameter and 36 inches high, at atmospheric pressure. (Data from reference 12.)

EFFECT OF SURFACE CONDITION AND COMPOSITION

Open plates in air.—Various data are available concerning the ignition of fuels dropped on heated metal plates in open air. Generally, the data indicate that the ignition temperature of an inflammable liquid is much higher when dropped on a heated metal plate in air than when dropped into a heated metal tube that confines the inflammable mixture to a high-temperature region. A comparison between the ignition temperatures of various liquid aircraft inflammables in these two environments is included in table I (a). The ignition temperatures of various inflammable liquids dropped on an electrically heated sheet-iron or nickel plate in air are presented in table I (b). According to reference 24, the same results were obtained by vaporizing the liquids and passing the vapor over the heated plates. Data from reference 25 indicate that the ignition temperatures of gasoline, gasoline-benzene mixtures, Diesel fuel, and motor oil placed on heated iron plates varied from 1325° to 1400° F, but were lowered to 1000° to 1025° F when copper plates were used. Droplets of lubricating oil at 750° F falling into a heated steel pipe were ignited at approximately 840° F, but Diesel fuel at a temperature of 425° F under the same conditions did not ignite below 1200° F. The low ignition temperatures of lubricating oils are assumed to be due to the greater instability of the complex molecules. Lowering of the ignition temperatures of the inflammable liquids by using copper plates may be due to the greater thermal conductivity of the copper and differences in the catalytic activity of the two surfaces.

Various investigators (reference 26) have indicated that heated surfaces in air, below temperatures of 950° F, do not present serious fire hazards when sprayed with small amounts of oil. Reference 27 indicates that oil explosions occur only when oil vapor is confined to a high-temperature region. Drops of oil placed on a plate heated to 1400° F would not ignite, but oil vapor ignited at 750° F. Similar results are presented in reference 26, which indicate that lubricating oils will not spontaneously ignite when dropped on either bare open metal plates or thin asbestos mats heated to 950° F. Light fractions, such as gasoline, immediately formed a ball and gradually distilled away. Heavier oils also vaporized (probably accompanied by simultaneous cracking); the vapors were diluted by air so quickly that no ignition could occur.

The results of actual tests conducted with a Napier Lion reciprocating engine are given in reference 12. Aviation gasoline vapors confined within the exhaust pipe and exposed to exhaust-pipe temperatures of 570° F ignited after a lag of 13 seconds. Outside the exhaust pipe, aviation gasoline did not ignite below temperatures of 850° F. Lubricating oil ignited at exhaust-pipe temperatures of 625° F. This apparent controversy over the ignition temperatures of oil or gasoline ignited by heated surfaces is due to the fact that liquid oils or gasolines falling on heated metal plates in open air are idealized experimental conditions that allow rapid diffusion of the inflammable vapors. The higher ignition temperature for the aviation gasoline is probably due to the rapid local cooling of the exhaust pipe in contact with the rapidly evaporating liquid. Heated metal pipes, exhaust manifolds, or enclosed heated areas of an aircraft engine may confine the inflammable vapors to high-temperature regions for ignition-lag periods corresponding to low-temperature ignition.

Varying surface compositions.—The ignition temperatures of inflammable mixtures ignited by heated surfaces are affected by the composition and the condition of the ignition surfaces. The effect of the composition of the ignition surfaces on the surface ignition temperatures of natural-gas–air mixtures is shown in figure 15. The various steels, copper, and Monel metal do not differ in their ignition effectiveness as much as catalytically active platinum differs from nickel. The abnormal effect of molybdenum is probably associated with the rapid oxidation properties of the metal. In all the experiments with molybdenum strips, dense clouds of oxides were formed. Tungsten, however, which oxidizes readily at high temperatures, did not oxidize vigorously until raised to temperatures higher than those required for surface ignition of the natural-gas–air mixtures. The following data, from reference 19, indicate the effect of the ignition-surface composition on the surface ignition temperatures of gasoline as determined in air by the dynamic crucible method:

Disk material (in silica crucible)	Surface ignition temperature (° F)
Platinum	878
Iron	833
Copper	788

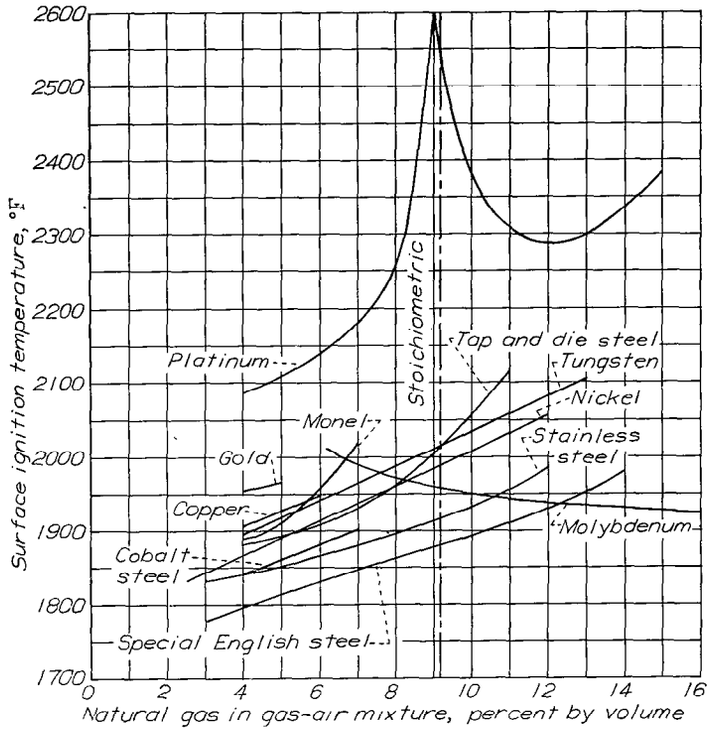


FIGURE 15.—Variation of surface ignition temperatures of natural-gas-air mixtures with percent of natural gas in mixture. Mixtures ignited by electrically heated metal strips. Size of metal strips, 4.25 by 0.50 by 0.04 inches. (Data from reference 11.)

Similar data are contained in table II concerning the effect of ignition-surface composition on the ignition temperatures of liquid fuels dropped into heated containers. In each case, catalytically inactive pyrex surfaces ignited inflammable mixtures at temperatures lower than those of metal surfaces. Discrepancies in ignition temperatures for the same substances in table II are probably due to different experimental techniques. Of the metal ignition surfaces with about the same degree of catalytic activity, those surfaces having the highest thermal conductivities had the lowest ignition temperatures. The effect of ignition-surface composition on the surface ignition temperatures of varying mixtures of a standard reference gasoline and benzene in air is indicated in figure 16. The ignition temperatures of the mixtures, excepting approximately 100-percent benzene, are 35° to 155° F greater for platinum surfaces than for quartz surfaces.

In similar experiments, the surfaces of greater catalytic activity or interstitial character must be hotter to ignite inflammable mixtures than surfaces of catalytic inactivity. Some references indicate that two types of combustion may be present in ignition by heated surfaces (1) a flameless, surface combustion, and (2) a gaseous combustion indicated by a flash. Combustion of a drop of liquid falling upon a surface that is not interstitial or porous in character or that is catalytically inactive occurs mostly in the gaseous phase with a minimum of surface combustion occurring. If the surface is highly catalytic or interstitial, however, it may be impossible for a flash to occur because most of the combustion may take place on the surface. Apparently, with all factors constant except the composition of the igniting surface, the surface ignition temperature of an inflammable mixture increases with increasing catalytic activity or interstitial character of the surface.

Rapid diffusion from the flameless reaction zones near the heated surfaces may explain the fact that higher surface ignition temperatures are required on catalytically active surfaces. Such rapid diffusion may diminish the concentration of fresh gas in the reaction zone below the limits for flame propagation at the surface temperature.

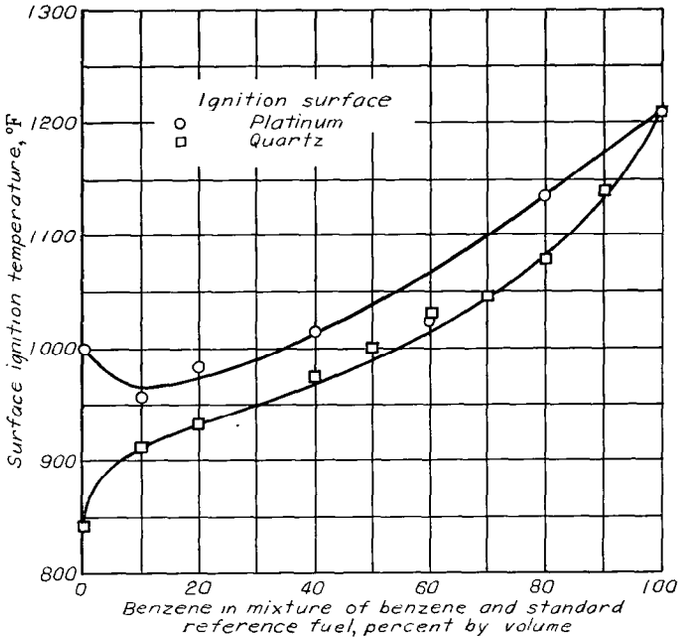


FIGURE 16.—Variation of surface ignition temperature of benzene-gasoline mixture in air at atmospheric pressure with various fuel compositions. Method of ignition, static crucible; ignition lag, 1 second. (Data from reference 28.)

The mixtures most difficult to ignite with the catalytically active platinum strips are the mixtures having approximately stoichiometric fuel-air ratios. With platinum ignition surfaces, the combustion products are almost completely oxidized, and the greatest thermal energy of the reaction occurs with mixtures of approximately stoichiometric fuel-air ratios. The thermal energy of the reaction accounts for the extremely high ignition temperatures of near stoichiometric mixtures of natural gas and air ignited by heated platinum surfaces. No effect of surface composition on the ignition temperatures of the three mixtures ignited by shot-in spheres of quartz or platinum is apparent in figure 11. Compared with platinum, quartz is catalytically inactive. The mixture composition in each case, however, is less or greater than the stoichiometric fuel-air ratio for each particular mixture; the mixtures are probably too far from the stoichiometric fuel-air ratios to be greatly affected by the composition of the ignition surface.

Varying surface conditions.—All the common metals having high melting points ignite inflammable mixtures with about equal facility except those on the surface of which scale or ash is formed. This scale or ash forming tendency is especially peculiar to iron. A possible explanation is that scale or ash upon a surface forms an insulating coating, which requires the surface to be heated to a much higher temperature for ignition than would otherwise be necessary. A gas film or layer on the inside of a container may act in the same manner.

According to reference 29, a stoichiometric mixture of methane and air introduced into a silica cylinder etched inside with hydrofluoric acid and maintained in a vacuum for 15 minutes ignited at 1085° F. The same mixture, placed in the cylinder following the evacuation of water vapor or carbon dioxide vapor, ignited at 1265° F. The surface ignition temperature of the mixture was increased by the adsorbed film of water vapor or carbon dioxide vapor.

EFFECT OF VARYING IGNITION SURFACE AREA

Heated plates.—Because the thermal energy required for ignition of an inflammable mixture is essentially constant, increasing the area of heat transfer results in a decrease of the surface temperature required for ignition of an inflammable mixture. This effect on a quiescent 7-percent mixture of natural gas in air ignited by electrically heated nickel surfaces is indicated in figure 17. From figure 17, it is apparent that a minimum surface ignition temperature exists for the mixture and this minimum ignition temperature cannot be decreased by indefinitely increasing the area of the ignition surface.

Heated wires.—Very fine wires electrically heated to incandescence may cause inflammation of explosive mixtures; but ignition of a methane-air mixture by an electrically heated platinum or tungsten wire is possible only in a narrow range of heating currents. Below this current range, flameless surface combustion occurs; above this range, the wires fuse without igniting the mixture. According to reference 30, the ignition of inflammable mixtures by heated platinum wires is not due to ionization, but to heat transfer alone, because ions do not appear until flame appears and no ions are formed during the flameless surface combustion.

Because of heat generated on its surface by flameless combustion, an electrically heated platinum wire surrounded by an inflammable mixture has a higher temperature than when surrounded by air. The mixture near the wire becomes heated and convection currents are set up. Ignition of the mixture occurs only if a portion of the mixture remains in contact with the heated wire for a period of time greater than the ignition lag. The convective effect is greatest with the mixtures having the highest thermal energies; that is, mixtures having compositions near stoichiometric fuel-air ratios (reference 31). Thus stoichiometric mixtures are in contact with the heated wires for the shortest periods of time and consequently have higher ignition temperatures than mixtures of other compositions. The ignition temperatures of the mixtures decrease with increasing diameter of the heated ignition wires, because of the greater ignition area.

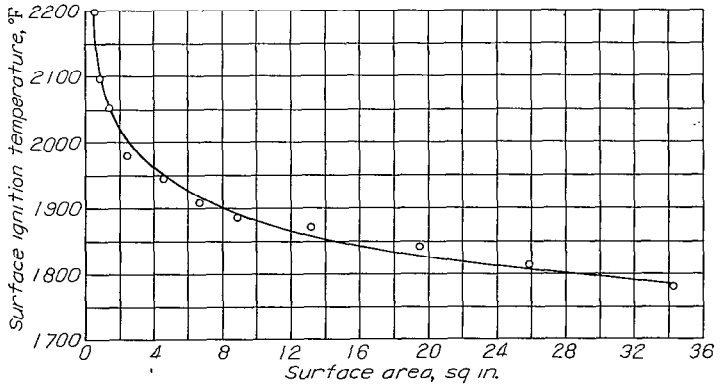


FIGURE 17.—Effect of surface area on surface ignition temperature of quiescent 7-percent mixture of natural gas and air. Ignition surface, electrically heated nickel. (Data from reference 11.)

In the investigation of flameless surface combustion reported in reference 32, 0.02 to 0.09 cubic centimeter of hexane, cyclohexane, cyclohexene, and benzene were separately introduced into an air atmosphere in a 400-cubic-centimeter cylinder heated to 221° F that contained a small electrically heated platinum wire. Heating of the wire to 572° F resulted in sudden increases of the wire temperature for a short period of time prior to inflammation of the mixtures. According to reference 31, small, heated tungsten wires exposed to inflammable mixtures are quickly oxidized and burst into flames immediately at high wire temperatures. The ignition of the mixture is caused by flames rather than by a heated surface.

Data obtained from reference 33 indicate that the limiting minimum diameters of heated wires capable of igniting inflammable methane-air mixtures are approximately 0.0079 and 0.0354 inch for platinum and iron wires, respectively. For wires of lesser diameters than these, it is assumed that a layer of oxygen molecules forms on the heated wire, and thermal energy sufficient to ignite the mixture cannot be conducted through the layer. Even in an unburned mixture of methane and air, a spiral piano wire heated to redness has been found to oxidize.

Heated particles.—Ignition of inflammable mixtures by small heated spheres shot into the mixture has already been discussed. Friction sparks and fusion sparks both fall into the category of small heated particles.

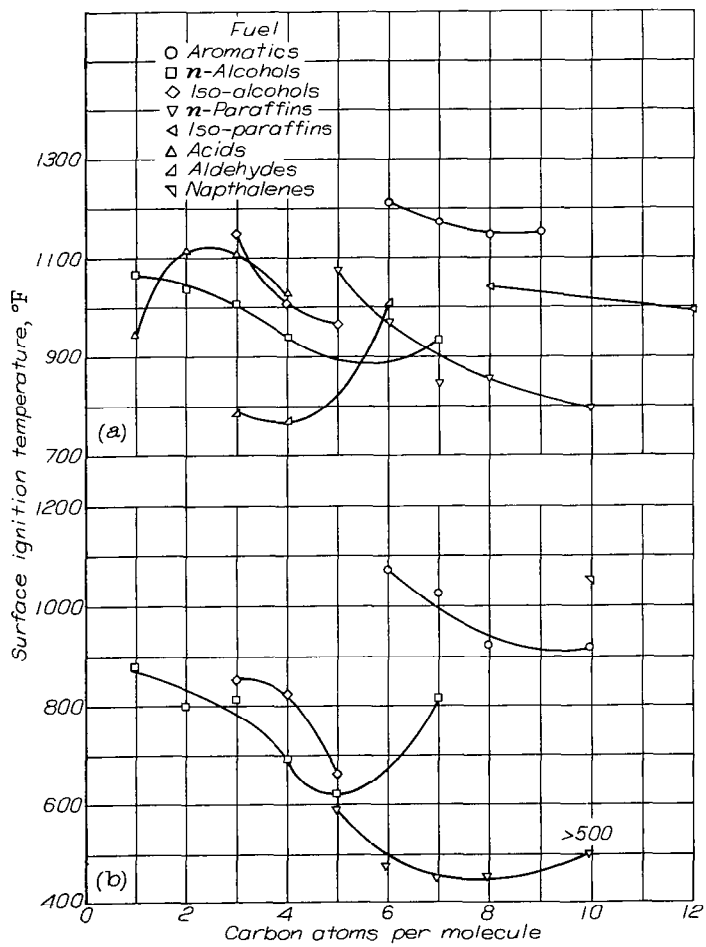
According to reference 34, although natural-gas–air mixtures can be ignited by friction sparks, it is improbable that natural gas can be ignited in the field by friction sparks. Reference 35 indicates that explosive mixtures of gasoline vapors and air at atmospheric pressure and temperatures of 70° to 120° F would not ignite when exposed to sparks produced by the impact breaking of piano wire, contact of two pieces of hardened steel, steel in contact with a rotating emery wheel, or sparks from red-hot steel. Such sparks ordinarily lack the thermal energy required to ignite inflammable mixtures. Ordinary white friction sparks produced by grinding steel in air are actually small metal particles, which oxidize or burn in air after being initially heated by being torn off in the grinding process. These sparks will not ignite petroleum vapors unless the metal is held to the wheel for a long time to preheat the metal and thereby increase the thermal energy of the spark. Alloy steel, in general, produces red friction sparks of low temperature, whereas some special alloys such as are used in cigarette lighters produce bright white sparks capable of igniting gasoline. Fusion sparks are small fused-incandescent particles derived from metals contacting wires through which current is passing. Because the ignition temperature of a mixture ignited by small heated particles increases rapidly with decreasing particle diameter, fusion sparks ordinarily are very feeble ignition sources.

EFFECT OF VARYING FUEL COMPOSITION

The ignition temperature of an inflammable mixture varies with the type of fuel and the amount of antiknock additives in the fuel. This report is primarily concerned with the effect of gasoline composition on ignition temperatures, but the effect of hydrocarbon families in addition to those that appear in gasoline are also included.

The variation of surface ignition temperature with the number of carbon atoms present per molecule for different hydrocarbon families is shown in figure 18. Under the same experimental conditions, the ignition temperatures of *n*-paraffin hydrocarbons decrease with a lengthening of the carbon chain, with the shortest chain hydrocarbons having the highest ignition temperatures. Iso-paraffins have higher ignition temperatures than the *n*-paraffins (fig. 18 (a)). The ignition temperatures of aromatic hydrocarbons are also higher than those of *n*-paraffins.

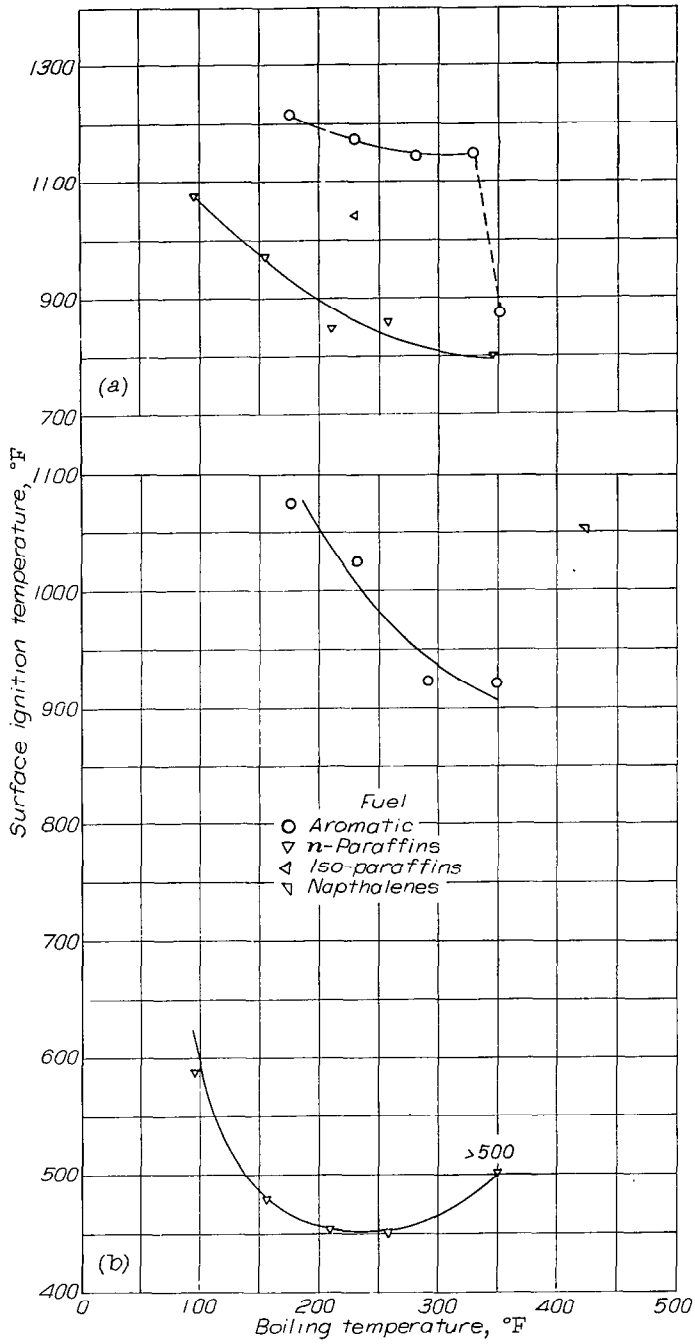
The surface ignition temperatures of various hydrocarbons are expressed as functions of the boiling temperatures in figure 19. Although the absolute value of the ignition temperature for the same hydrocarbon differs with the reference,



(a) Ignition temperatures determined by static crucible method. Ignition surface, platinum; ignition lag, 1 second; data from reference 36.

(b) Data from reference 37.

FIGURE 18.—Variation of surface ignition temperatures of several fuels in air at atmospheric pressure with number of carbon atoms per molecule.



(a) Method of ignition, static crucible; ignition surface, platinum; ignition lag, 1 second; data from reference 36.

(b) Data from reference 37.

FIGURE 19.—Effect of boiling temperature on surface ignition temperatures of several fuels in air at atmospheric pressure.

trends are similar for the same hydrocarbon families. The effect of fuel composition on the surface ignition temperatures of mixtures of isooctane and heptane ignited in air on a platinum surface by the static crucible method is shown in figure 20. In reference 38, it is stated that no exact relation exists between the octane number and the ignition temperature of a fuel, but figure 20 and table III indicate that the ignition temperatures of unleaded fuels generally increase with increasing octane number.

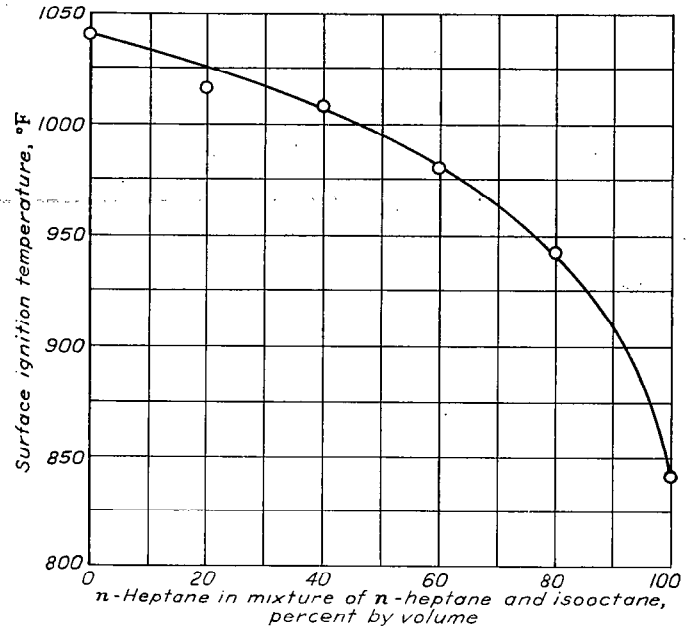


FIGURE 20.—Effect of varying fuel composition on surface ignition temperatures of *n*-heptane—iso-octane (2,2,4-trimethylpentane) mixture as determined in air at atmospheric pressure. Method of ignition, static crucible; ignition surface, platinum; ignition lag, 1 second. (Data from reference 28.)

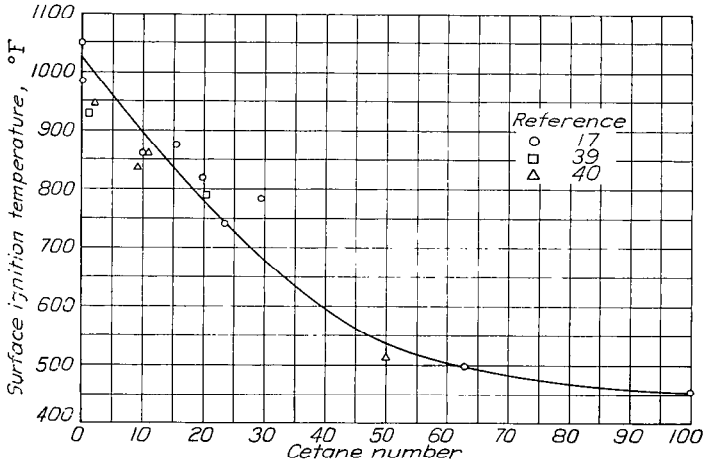


FIGURE 21.—Effect of cetane number on surface ignition temperature of various fuels in air at atmospheric pressure. Cetane numbers are converted A.S.T.M.-CFR numbers.

The ignition temperatures of unleaded fuels in air are also generally increased by additions of tetraethyl lead. Table IV shows the effect of additions of tetraethyl lead on the ignition temperatures of several fuels. A relation exists between the cetane numbers and the surface ignition temperatures of various fuels, as indicated by figure 21. The cetane numbers of the fuels were converted from octane numbers, given in reference 41, by the method given in reference 42. The ignition temperatures of the various fuels increase with decreasing fuel quality or cetane number.

EFFECT OF VARYING PRESSURE

Increased pressure decreases the ignition temperatures of inflammable mixtures. The effect of pressure on the ignition temperatures of various hydrocarbons is shown in figures 22 to 24. The chamber ignition temperature of gasoline in air

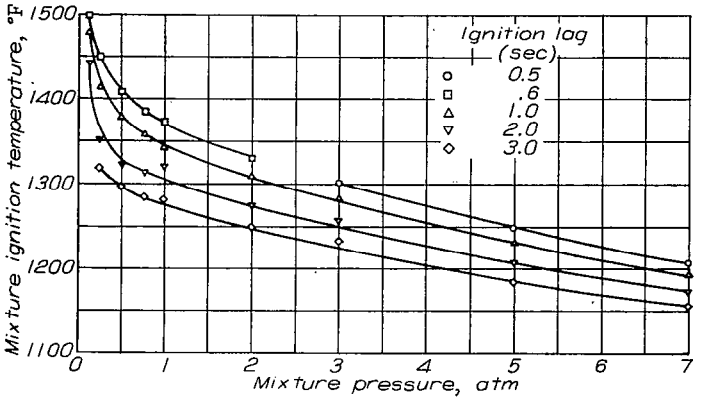


FIGURE 22.—Effect of mixture pressure on mixture ignition temperature of methane in air. Method of ignition, dynamic heated tube. (Data from reference 3.)

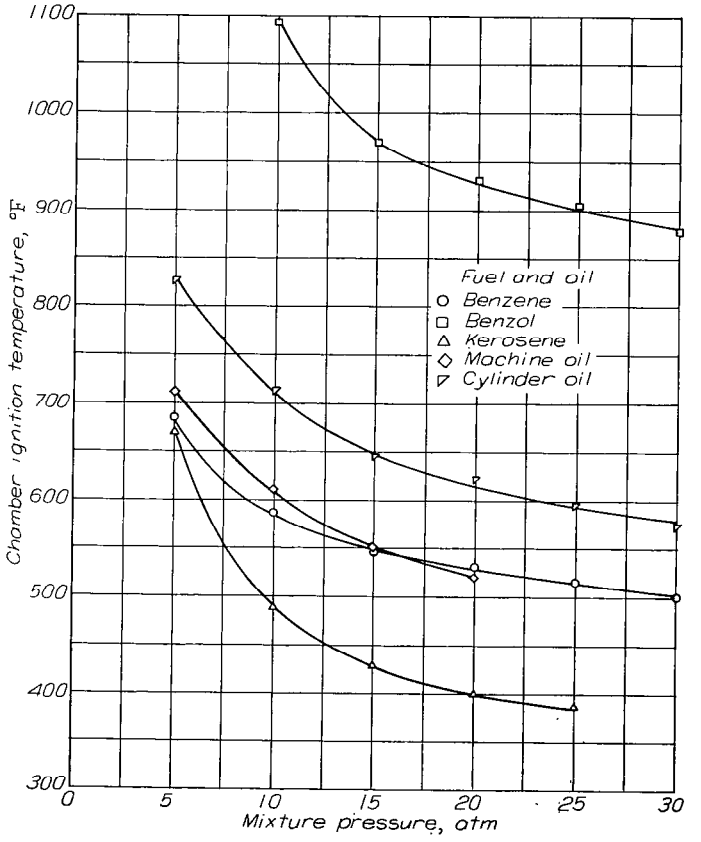


FIGURE 23.—Effect of mixture pressure on chamber ignition temperatures of several fuels and oils in air. Method of ignition, bomb. (Data from reference 43.)

as determined by the bomb method without spraying decreases from approximately 705° F at a pressure of 2.2 atmospheres to approximately 450° F at 10 atmospheres (fig. 24).

EFFECT OF DILUENTS

Figures 4 and 5 indicate the effect of nitrogen as a diluent on the mixture ignition temperatures of inflammable mixtures ignited by the dynamic heated-tube method. The ignition temperatures of the mixtures increase with decreasing amounts of oxygen. This effect is in general agreement with the statement that the ignition temperatures of fuels are generally less in oxygen than in air. In the low ignition-

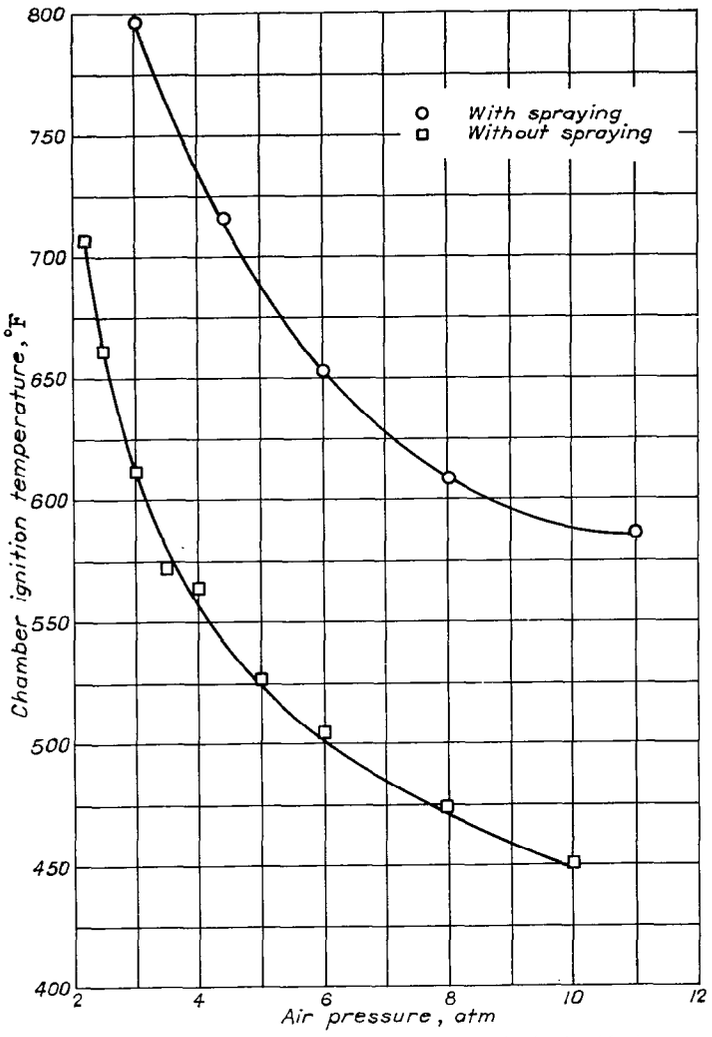


FIGURE 24.—Variation of chamber ignition temperature of gasoline in air with air pressure. Method of ignition, bomb. (Data from reference 43.)

temperature range of figures 4 and 5, however, the effect of inert gases is negligible. Regardless of the percentage of inert gas in the mixture, the ignition temperature in the low ignition-temperature range is approximately constant.

The ignition temperatures and limits of inflammability of gasoline and lubricating oils are dependent on the conditions and methods of experiment; these properties of gasolines and lubricating oils as obtained by different investigators are included in tables V and VI.

II—IGNITION BY ELECTRIC SPARKS AND ARCS

A study of ignition of inflammable mixtures by electric sparks and arcs involves an understanding of the nomenclature of spark-ignition systems. Definitions of terms encountered in the contemporary literature, which pertain to electric spark and arc ignition, are presented in the following paragraphs.

TERMINOLOGY

CAPACITANCE SPARKS

Capacitance sparks are produced by the discharge of charged condensers. According to reference 44, capacitance sparks are usually bright, may be of short duration, and exhibit a spectrum that corresponds to the spectrum of the gas mixture in which the spark occurs. The current in a capacitance spark may be very large; however, the total energy transferred in the spark may be small because of the short duration of the spark. The total energy of a capacitance spark, expressed as the energy required in a circuit to produce the spark, is

$$E=\frac{1}{2}C(V_2^2-V_1^2) \tag{3}$$

where

C capacitance of discharged condenser, farads
E energy dissipated in spark, joules
V_1 extinction potential remaining after spark has been dissipated because of weakening of field and depletion of ions, volts
V_2 circuit potential immediately prior to spark, volts

Generally, the extinction potential V_1 is so small that it can be disregarded. If V_2 is very small, however, V_1 may be important. Considerable energy losses may occur in the electric circuits through skin effects in the condenser plates and conductors especially if solid dielectrics are used. For this reason, it has been recommended that air condensers be used in electric circuits to determine the minimum spark-ignition energies of incendiary capacitance sparks.

INDUCTANCE SPARKS

Also known as low-tension sparks, inductance sparks are often obtained by breaking a wire in an inductive electric circuit or from magnetos or ignition coils. These sparks are generally not as bright in appearance as capacitance sparks and exhibit a spectrum corresponding to the spectrum of the vapor of the metal electrodes. The duration of inductance sparks can be relatively long compared with the duration of capacitance sparks; the total electric energy transferred in such sparks may therefore be large. Like the capacitance spark, the energy dissipated in an inductance spark is difficult to measure, but can be expressed as,

$$E=\frac{1}{2}Li^2 \tag{4}$$

where

E energy dissipated in spark, joules
i current in circuit prior to spark, amperes
L inductance of electric circuit, henrys

According to reference 44, the total energy dissipated in the spark may be less or greater than $\frac{1}{2}Li^2$. If the spark is extinguished before the available electromagnetic energy is dissipated, the total energy dissipated in the spark will be less than $\frac{1}{2}Li^2$. The total energy dissipated in the spark may be greater than $\frac{1}{2}Li^2$ if the potential across the break is enough to maintain the spark.

FUSION SPARKS

Fusion sparks are small incandescent particles and are treated in the section IGNITION BY HEATED SURFACES.

MINIMUM SPARK-IGNITION ENERGY

The minimum spark-ignition energy of an inflammable mixture is the total electric energy stored in an electric circuit at the initiation of the weakest spark just capable of ignition of the mixture. Essentially, this energy is the energy transmitted to the gas between the electrodes as heat and ionization.

QUENCHING DISTANCE

The quenching distance of any electrode configuration is the minimum electrode spacing below which the reaction initiated in a hydrocarbon-air mixture by an incendiary spark is quenched.

The amount of energy in any of the different type sparks is difficult to measure exactly. Most of the results are therefore reported as the energy required in an electric circuit capable of producing an incendiary spark. This report is concerned with the minimum spark-ignition energy required to ignite a gasoline-air mixture and the minimum electrode spacing below which the reaction initiated in a gasoline-air mixture by an incendiary spark is quenched. These data are not extensive in the literature; however, knowledge pertaining to the spark ignition of the lighter hydrocarbons is quite extensive, and many of these results are included herein.

The spark-ignition process has been defined as an ionization process, a thermal process, or a combination of the two processes. Regardless of the definition of the type of process, the minimum spark-ignition energy of an inflammable mixture depends on mixture composition, pressure, temperature, velocity, spark duration, and electrode size, material, spacing, and configuration. Ignition lag, when applied to spark ignition, is approximately zero, because of the high temperature of the spark.

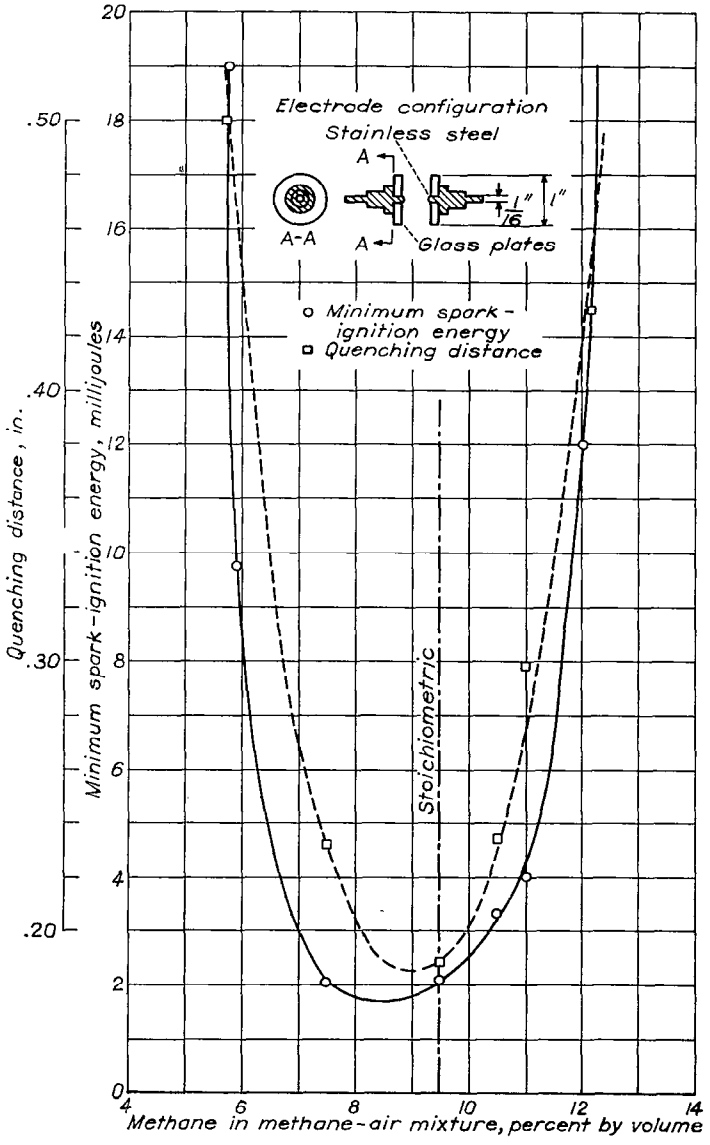


FIGURE 25.—Effect of mixture composition on minimum spark-ignition energy and quenching distance of methane-air mixtures at temperature of 77° F and pressure of ¼ atmosphere. (Data from reference 45.)

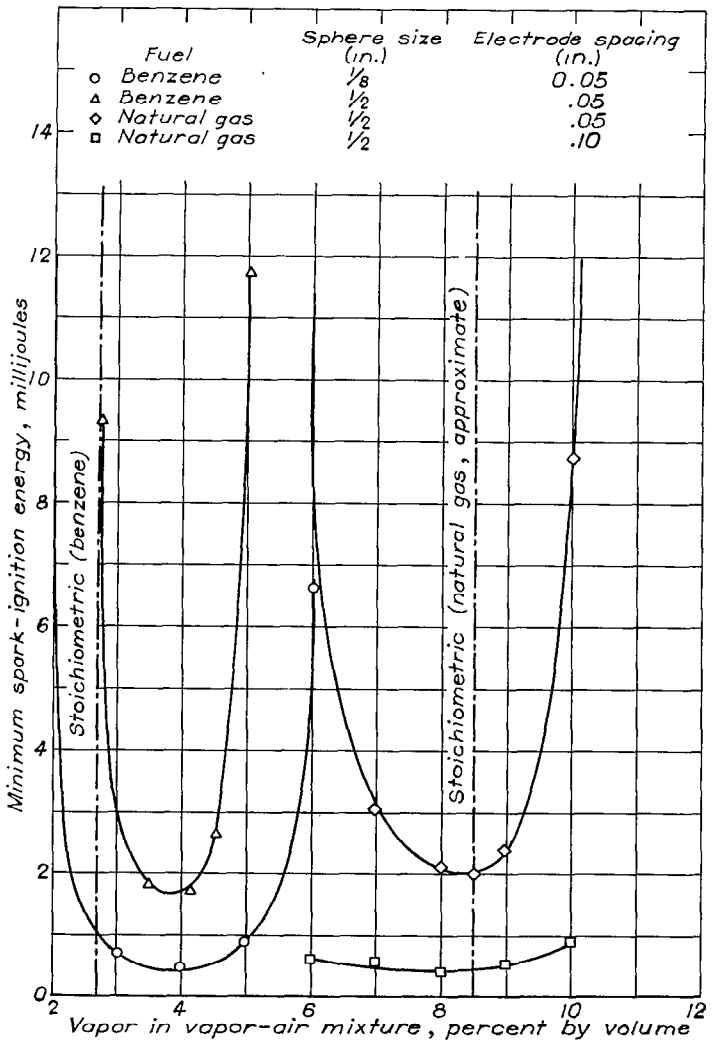


FIGURE 26.—Effect of mixture composition on minimum spark-ignition energy of benzene-air and natural-gas-air mixtures at room temperature and pressure of 1 atmosphere. Spherical stainless-steel electrode configurations. (Data from reference 46.)

EXPERIMENTAL RESULTS IN PUBLISHED LITERATURE

The ignition of fires in aircraft by electric sparks and arcs depends generally on the energy available in the spark. Whether the spark-ignition energy is capable of ignition depends on various experimental conditions. The manner in which results are presented here is similar to the manner in which heated-surface ignition results were presented; that is, the results are accompanied by data specifying the experimental conditions.

CAPACITANCE SPARKS

Effect of mixture composition.—The effect of mixture composition on the minimum spark-ignition energy of several different quiescent mixtures ignited by sparks from different electrode configurations is shown in figures 25 and 26. The curve of minimum spark-ignition energy, plotted against mixture composition for a methane-air mixture at a temperature of 77° F and a pressure of ⅓ atmosphere (fig. 25), passes through a minimum of approximately 1.7 millijoules at approximately 8.4 percent by volume of methane in air, when 1/16-inch stainless-steel electrodes embedded in 1-inch glass disks are used. Similar values for other mixtures are given in the following table for an approximate temperature of 77° F and pressure of 1 atmosphere. Stainless-steel electrodes were used except for methane, which was investigated by using stainless-steel electrodes embedded in 1-inch glass disks.

Inflammable	Mixture vapor in air, (percent by volume)	Electrode diameter (in.)	Electrode configuration	Electrode spacing (in.)	Least energy (millijoules)	References
Benzene	3.85	⅛	Spherical	0.05	0.4	46
Benzene	3.85	½	Spherical	.05	1.7	46
Natural gas	8.00	⅛	Spherical	.10	0.4	46
Natural gas	8.40	½	Spherical	.05	2.0	46
Methane	10.00	1/16	Hemispherical	....	0.7	47

For each of these inflammable mixtures, well defined upper and lower limits of inflammability exist.

The data given in the following table (reference 48) indicate that the minimum spark-ignition energies of different quiescent hydrocarbon-air mixtures at 77° F and pressure of 1 atmosphere ignited by capacitance sparks from the same electrode configuration do not differ greatly:

Inflammable	Percent of fuel in fuel-air mixture by volume	Least energy (millijoules)
Methane	8.45	0.28
Ethane	6.61	.25
Propane	5.07	.26
n-Butane	4.53	.26
n-Hexane	3.64	.24
n-Heptane	3.36	.25
Cyclopropane	6.34	.18
Cyclohexane	3.94	.24
Benzene	4.67	.21
Diethyl ether	5.30	.19

The effect of mixture composition on the minimum spark-ignition energies of flowing propane-air mixtures at a pressure of 3 inches of mercury absolute is indicated in figure 27. The general shapes of the curves, for the three mixture velocities plotted, are much the same as the shapes of curves for various quiescent mixtures.

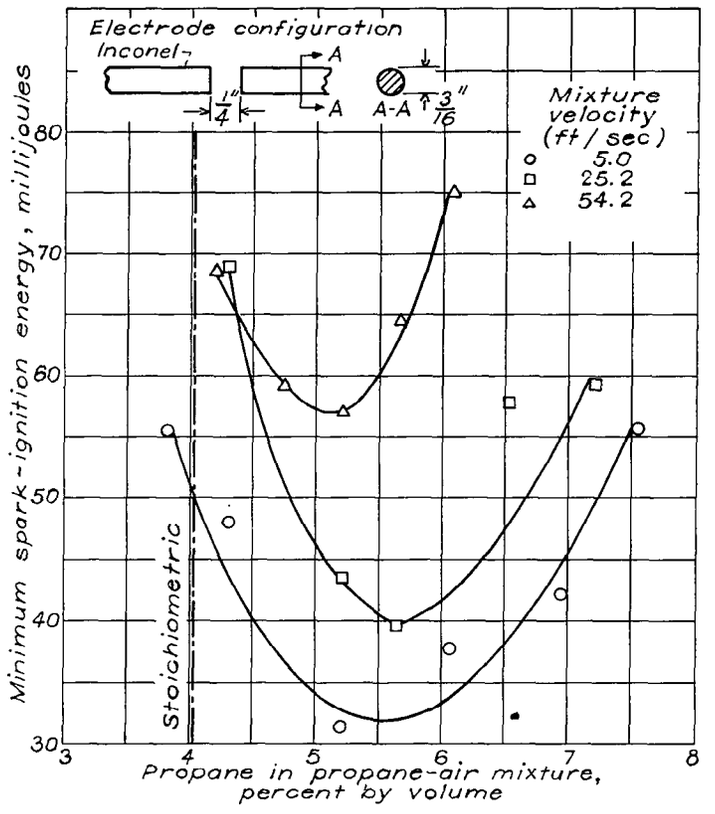
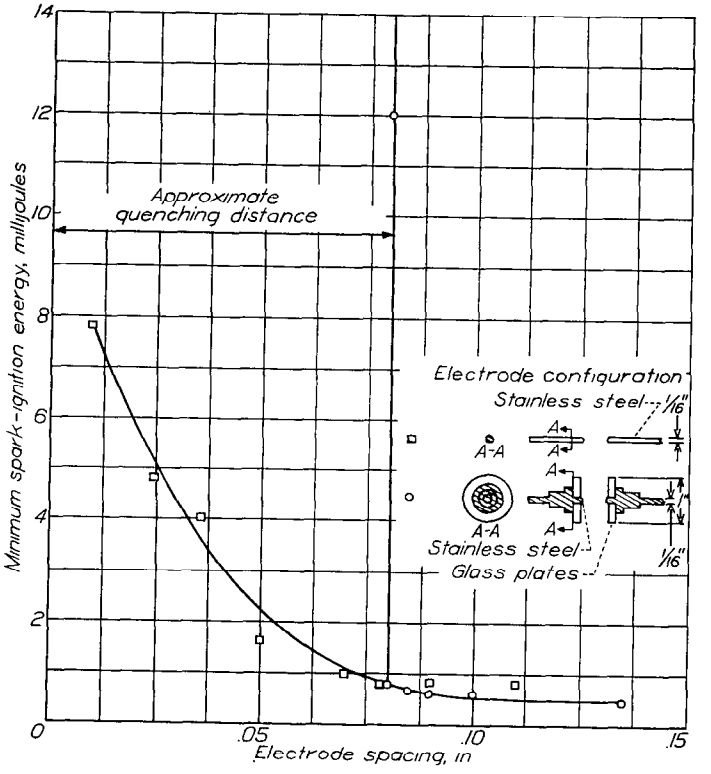


FIGURE 27.—Effect of mixture composition and velocity on minimum spark-ignition energy of flowing propane-air mixtures at temperature of 80° F and pressure of 3 inches mercury absolute. Electrode spacing, 0.25 inch; capacitance-spark duration, 600 to 900 microseconds. (Data from reference 49.)

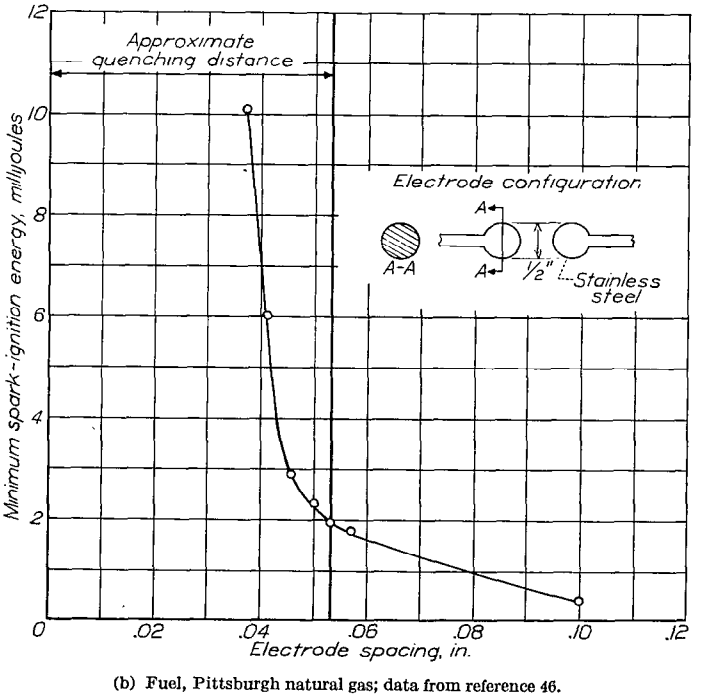
Effect of electrode spacing.—The effect of varying electrode spacings of different electrode configurations on the minimum spark-ignition energies of various inflammable mixtures is shown in figure 28. A critical electrode spacing exists for each electrode configuration. The minimum spark-ignition energy required to ignite a mixture is approximately constant for electrode spacings greater than the critical spacing. Greatly increased electrode spacings or spacings less than the critical spacing increase the required minimum spark-ignition energy of a mixture. According to reference 45, the critical electrode spacing represents the spacing below which the chemical reaction initiated by the initial inflammation is quenched by the cooling effect of the spark electrodes and is analogous to the diameter of the largest tube through which flame will not propagate. The minimum spark-ignition energies of a stoichiometric mixture of natural gas and air are approximately 0.45 millijoules for electrode spacings greater than the critical spacing or quenching distance of approximately 0.08 inch for two electrode configurations. When the electrode spacing is decreased to less than the quenching distance, the minimum spark-ignition energy increases gradually if rounded electrodes are used and abruptly if rounded electrodes embedded in glass are used. The abrupt change in the case of the disk electrode configuration may be due to the large cooling area of the glass disks. The quenching distance of one electrode configuration varies with composition of a methane-air mixture at a temperature of 77° F and a pressure of ⅓ atmosphere, as indicated in figure 25. A quenching distance of approximately 0.089 inch exists for a glass-disk electrode configuration igniting a 9 percent (by volume) mix-

ture of methane and air at a temperature of 77° F and atmospheric pressure (reference 50).

Under the same atmospheric conditions, ½-inch spherical stainless-steel electrodes and 5/16-inch hemispherical brass electrodes have exhibited quenching distances of approximately 0.053 inch in the spark ignition of approximately 8.5 percent by volume mixtures of natural gas and air and



(a) Fuel, natural gas; data from reference 45.



(b) Fuel, Pittsburgh natural gas; data from reference 46.

FIGURE 28.—Effect of varying electrode spacing on minimum spark-ignition energy of approximately 8.5 percent by volume mixture of fuel and air at atmospheric pressure and temperature.

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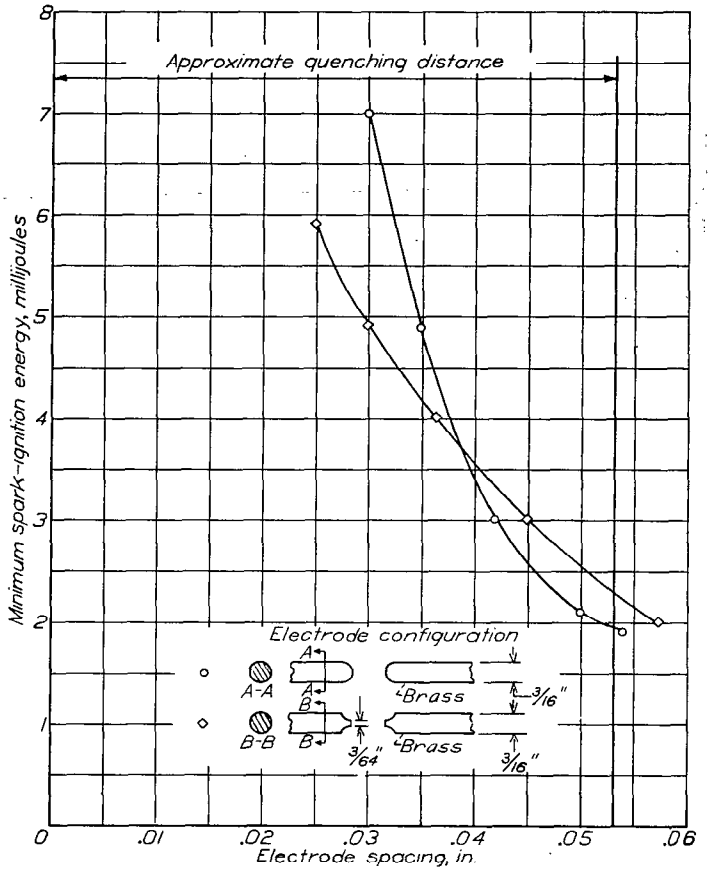


(c) Fuel, methane; data from reference 44.

FIGURE 28—Continued.

methane and air, respectively (fig. 28 (b) and 28 (c)). Quenching distances increase with increasing electrode size and thermal conductivity of the electrode material, owing to the increased cooling effect. Increasing the electrode size and electrode spacing for the same inflammable mixture increases the minimum spark-ignition energy required to ignite the mixture, because of the larger cooling area. For the same reason, the inflammability range is smaller when determined with large electrodes than with small ones (fig. 26).

Effect of electrode material and configuration.—With the exception of the relative effect of varying the thermal conductivity of the electrodes, varying the electrode material has no significant effect on the ignition of inflammable mixtures by capacitance sparks. Ignition of gaseous mixtures by sparks from platinum, nickel, zinc, aluminum, lead, brass, and steel electrodes was unaffected by changes in the electrode material (references 44 and 51). Ignition of the mixture was affected by the changes in electrode configuration.

Effect of spark potential.—Generally, the minimum spark-ignition energy of an inflammable mixture is practically independent of the spark potential of capacitance sparks. The same spark-ignition energy, regardless of the potential and capacitance changes in the circuit, ignites mixtures of the same composition. Some references indicate that the minimum spark-ignition energy required to ignite an inflammable mixture decreases with increasing spark potential. These data are insignificant in accordance with the results reported

in reference 50. When the sparking potential of capacitance sparks was varied from 1.6 to 5.8 kilovolts the minimum spark-ignition energies required to ignite methane-air mixtures was relatively unaffected by potential variations. Most of the references agree that it is the electrode configurations and electrode spacings that determine the minimum spark-ignition energies of capacitance sparks capable of igniting inflammable mixtures.

Effect of mixture velocity and spark duration.—According to reference 49, the minimum spark-ignition energy required to ignite flowing propane-air mixtures at low pressures increases approximately linearly with mixture velocity. This phenomenon is graphically shown in figure 29 for a 5.2 percent by volume mixture of propane in air at pressures of 2, 3, and 4 inches of mercury absolute. The relatively high ignition energies are due to the very low mixture pressures.

Minimum spark-ignition energies of flowing propane-air mixtures increase with spark duration as shown in figure 30. The relation is not linear, being approximately of the form

$$E=Kt^n \qquad (5)$$

where

E minimum spark-ignition energy
K constant
n constant <1
t spark duration

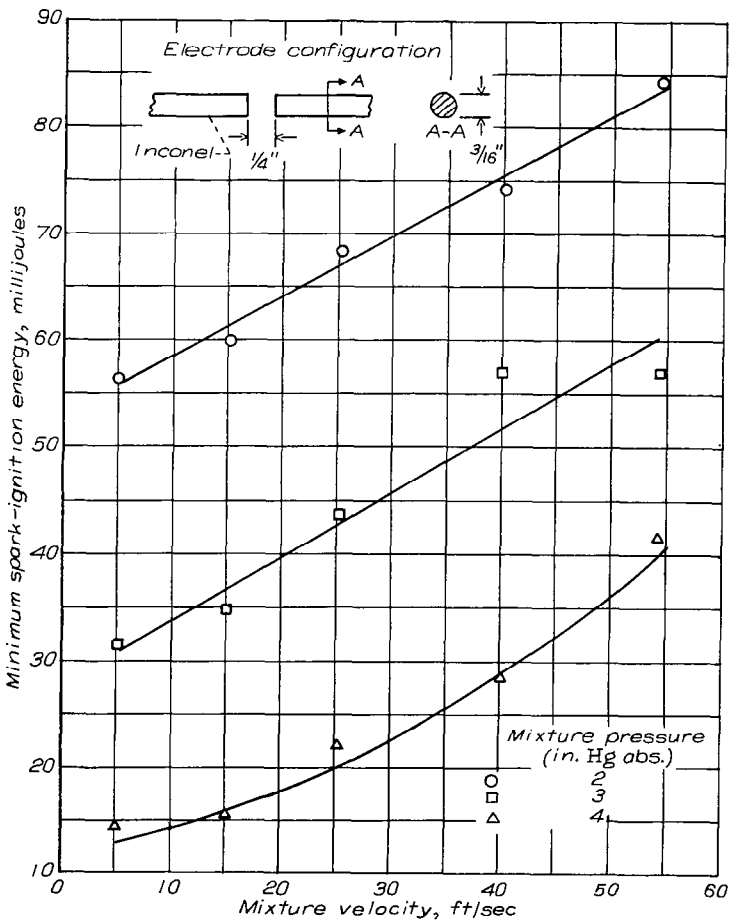


FIGURE 29.—Effect of mixture velocity and pressure on minimum spark-ignition energy of flowing 5.2 percent by volume mixture of propane in air at temperature of 80° F. Electrode spacing, 0.25 inch; capacitance-spark duration, 600 to 800 microseconds. (Data from reference 49.)

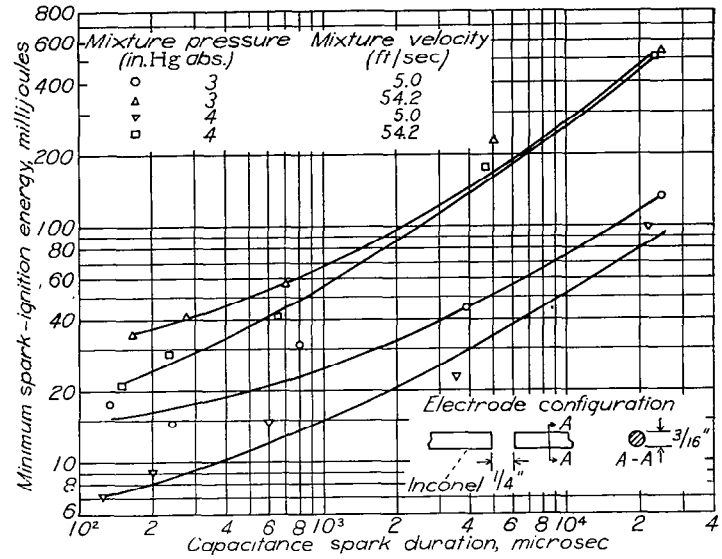


FIGURE 30.—Effect of capacitance-spark duration on minimum spark-ignition energy of flowing 5.2 percent by volume mixture of propane in air at temperature of 80° F. Electrode spacing, 0.25 inch. (Data from reference 49.)

Electrostatic sparks.—Electrostatic sparks are a special type of capacitance spark. Electrostatic charges capable of spark production can be accumulated by friction, impact, pressure, cleavage, induction, successive contact and separation of unlike surfaces, one of which is generally an insulator, and transference of inflammable fluids and gases from one container to another. Air temperatures appear to have no significant effects on the charges accumulated, but increasing humidity tends to prevent accumulation of high potential electrostatic charges. The potential of electrostatic charges accumulated by liquids flowing in tubes decreases with decreasing liquid pressures.

INDUCTANCE SPARKS

Effect of mixture composition.—The effect of mixture composition on the minimum spark-ignition energies of inductance sparks is indicated in figure 31 for two hydrocarbon-air mixtures. Because the electric circuit inductance is difficult to measure, the results are expressed as the minimum ignition current with a constant electrode spacing. The effect of mixture composition is approximately the same for inductance sparks as for capacitance sparks. Well-defined limits of inflammability exist with both types of igniting spark. Approximately 0.59 ampere primary current in the inductive circuit produces a spark capable of igniting an 8.3 percent by volume mixture of methane in air. An ignition current of approximately 0.475 ampere in the same electric circuit will produce an inductive spark capable of igniting a 4.2 percent by volume mixture of *n*-butane in air. These data were obtained at atmospheric pressure and temperature. According to available data, the ranges of inflammability determined for capacitance sparks are slightly greater than those determined for inductance spark ignition.

Effect of electrode spacing.—Because of the manner in which inductance sparks often occur, few data are available that indicate the effect of electrode spacing on the ignition of inflammable mixtures. The variation of spacing of inductance-

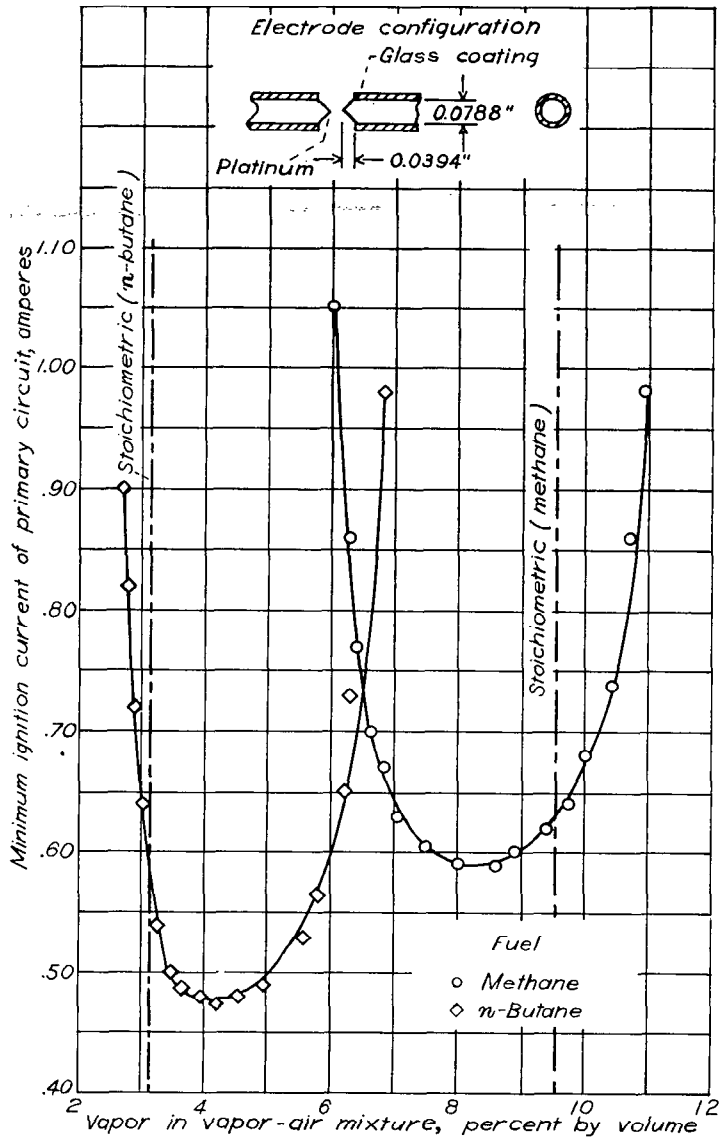


FIGURE 31.—Effect of mixture composition on minimum ignition currents of primary circuits producing inductance sparks capable of igniting methane-air and *n*-butane-air mixtures at atmospheric pressure and temperature. Electrode spacing, 0.0394 inch. (Data from reference 52.)

spark electrode configurations with mixture composition is indicated in figure 32 as being similar to the variation with capacitance-spark electrode configurations. A minimum electrode spacing of approximately 0.043 inch is indicated for an 8.5 percent by volume mixture of methane in air ignited by inductance sparks from the particular electrode configuration.

Effect of electrode material.—Unlike the effect of electrode material on capacitance-spark ignition, the minimum spark-ignition energies of inflammable mixtures ignited by inductance sparks are affected by material changes in the electrode configuration. Ethane-air and carbon-monoxide–air mixtures were ignited at atmospheric temperature and pressure using electrodes of platinum, nickel, copper, aluminum, and iron (reference 54). Decreasing density of the electrode material generally increased the ignitibility of the inflammable mixtures. The least amount of energy dissipated in an inductive spark capable of igniting an inflammable mixture occurs with spark electrodes of the lightest metal.

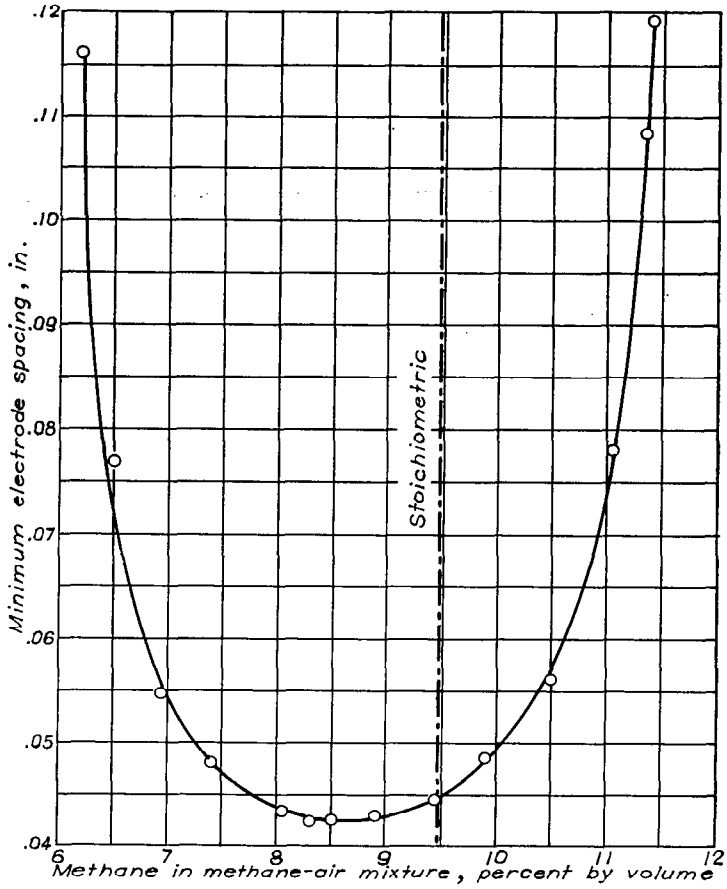


FIGURE 32.—Effect of mixture composition on minimum spacing of electrode configuration producing inductance sparks capable of igniting methane-air mixtures at atmospheric pressure and temperature. Electrode configuration, 0.394-inch-diameter platinum disk and sharply pointed platinum cone; primary circuit current, 1.0 ampere. (Data from reference 53.)

Effect of circuit inductance and potential.—The energy required for ignition of an inflammable mixture by inductance sparks depends on the inductance, the current, and the potential in the electric circuit prior to the spark. The amount of energy required to ignite the mixture is substantially constant, but larger amounts of energy may be indicated if a large portion of the measured energy is dissipated in the inductance coil as core losses. The following data from reference 55 indicate the effect inductance and current in an electric circuit have on the measured minimum spark-ignition energy required to ignite a mixture of coal gas and air at atmospheric pressure and temperature.

Number of layers in inductance-coil winding	Core of coil	Circuit inductance (henrys)	Circuit current (amperes)	Spark-ignition energy (millijoules)
14	Air	0.01	0.35	0.6
14	Straight iron bar	.07	.15	.8
14	Rectangular iron frame	.56	.09	2.3

Inductance sparks from electric circuits of low potential require more measured spark-ignition energy to ignite the same inflammable mixture than inductance sparks from similar electric circuits of higher potential, as indicated by the following data from reference 56 for inductance-spark

ignition of an 8.5 percent by volume mixture of methane in air at atmospheric temperature and pressure.

Circuit potential (volts d. c.)	Circuit inductance (henrys)	Circuit current (amperes)	Spark-ignition energy (millijoules)
4	0.02144	0.77	6.35
220	.02144	.35	1.30
4	.012	1.025	6.30
220	.012	.4	.96

The amount of energy dissipated in an inductance spark consists of two parts: the energy stored in the electric circuit prior to the spark and the continued supply of energy from the circuit potential. The amount of energy stored in the electric circuit prior to the inductance spark is the only spark-ignition energy measured. The spark-ignition energy supplied by the electric circuit potential to an inductance spark increases with increasing circuit potential. Thus, inductance sparks from electric circuits of low potential require greater measured amounts of spark-ignition energy $\frac{1}{2}Li^2$ than sparks from circuits of high potential to ignite similar inflammable mixtures.

Effect of type of current in circuit.—The type of current in the electric circuit, alternating or direct, has no significant effect on the ignition ability of inductance sparks. No difference in the ignition ability of alternating or direct-current inductance sparks has been found by the investigators of reference 57, who ignited fire-damp—air mixtures at atmospheric pressure and temperature. The following data from reference 56 indicate the negligible effect of current type on the incendiarism of inductance sparks igniting an 8.5-percent (by volume) methane-air mixture at atmospheric conditions:

Type of current	Current frequency (cps)	Ignition current (amperes)
Direct	---	0.415
Alternating	68	.410 crest values
Alternating	200	.420 crest values

EFFECT OF GAS PRESSURES AND TEMPERATURES

The effects of temperature and pressure are the same for both capacitance and inductance sparks; the following discussion therefore applies to all sparks.

Varying pressure.—The ignition of inflammable mixtures is significantly affected by varying mixture pressures and temperatures. The inflammability range of different mix-

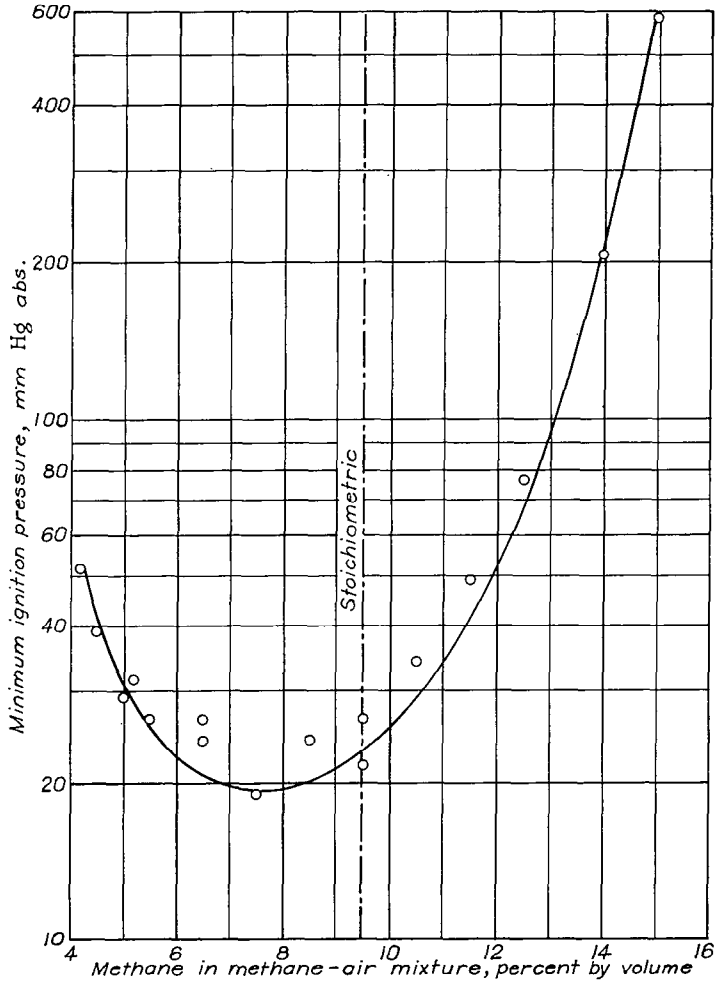


FIGURE 33.—Effect of mixture composition on minimum ignition pressures of methane-air mixtures at temperatures of 78° to 87° F. Method of ignition, bomb; electrode configurations, spark-plug; electrode spacing, 0.110 inch; capacitance-spark ignition energy, 8640 millijoules; volume of bomb, 750-cubic-centimeters. (Data from reference 58.)

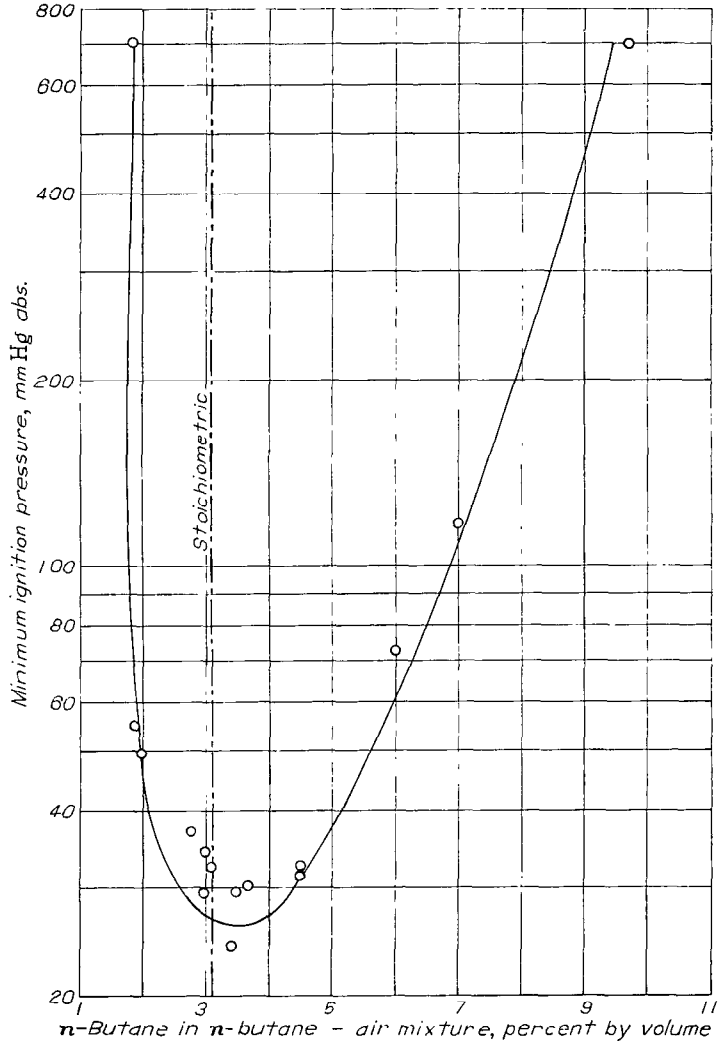
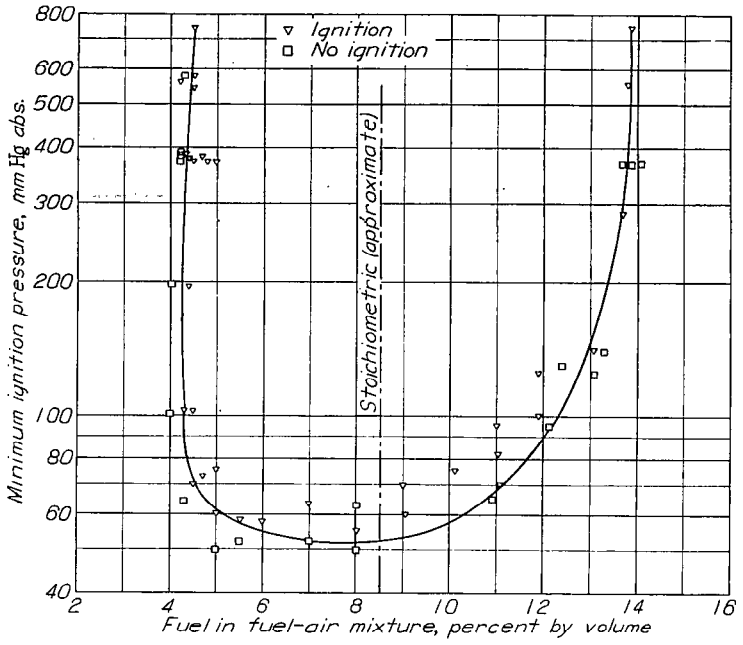
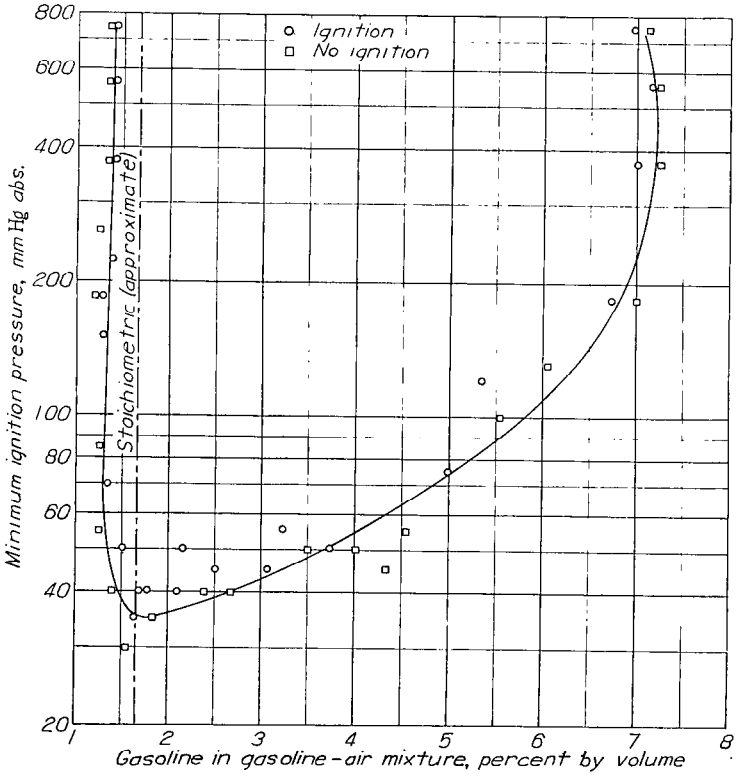


FIGURE 34.—Effect of mixture composition on minimum ignition pressures of *n*-butane–air mixtures at temperatures of 73° to 84° F. Method of ignition, bomb; electrode configuration, spark-plug; electrode spacing, 0.110 inch; capacitance-spark ignition energy, 8640 millijoules; volume of bomb, 750-cubic-centimeters. (Data from reference 58.)



(a) Fuel, natural gas; data from reference 59.



(b) Fuel, 100-octane gasoline; ignition by hydrogen flame, electric spark, gun cotton, or heated platinum wire; data from reference 7.

FIGURE 35.—Effect of mixture composition on minimum ignition pressures of two fuel-air mixtures.

tures is reduced by decreasing mixture temperatures and pressures. This effect of mixture pressure on the limits of inflammability of several inflammable mixtures is shown in figures 33 to 35. The minimum ignition pressure or the minimum mixture pressure of methane below which ignition is no longer possible, exists at mixture compositions less than stoichiometric; reference 58 indicates that the same relation is true for hydrogen. The minimum ignition pressures of heavier hydrocarbons, such as propane and *n*-butane, occur at mixture compositions greater than stoichiometric. These phenomena may be due to the diffusivity of air being less than the diffusivities of methane or hydrogen, but greater than those of propane or *n*-butane. The minimum ignition pressures do not vary greatly for hydrocarbons in the range of molecular weights given in the following table taken from reference 58 which gives the minimum ignition pressures of hydrocarbon-air mixtures as determined in a 750-cubic-centimeter metal bomb (mixture temperature, 75° to 85° F; electrode spacing, 0.110 inch; capacitance-spark ignition energy, 8640 millijoules).

Hydrocarbon	Minimum ignition pressure (mm Hg abs.)
Hydrogen	11.5
Methane	19.0
Butadiene-1,3	21.0
Butenes-2	29.0
n-Butane and iso-butane	29.0
Benzene	28.0
2,4-Dimethyl-1,3-pentadiene	33.0
n-Nonane	33.0

Various investigators have found higher minimum ignition pressures for different hydrocarbons, as indicated in figure 35 (a), for natural gas. Differences in results are due to different experimental techniques. Little data expressing the effect of varying mixture pressures and temperatures on the incendiary properties of gasoline-air mixtures are available.

According to reference 60, the minimum ignition pressure of various gasoline-air mixtures ignited in vessels of 0.425, 1.09, and 125.0 cubic-foot capacity by sparks or hot platinum wires is 33 millimeters of mercury absolute at ordinary ambient temperatures. Close agreement with these results is evident in figure 35 (b). The minimum ignition pressure of mixtures of 100-octane gasoline and air ignited by four different methods at atmospheric temperatures is 35 milli-

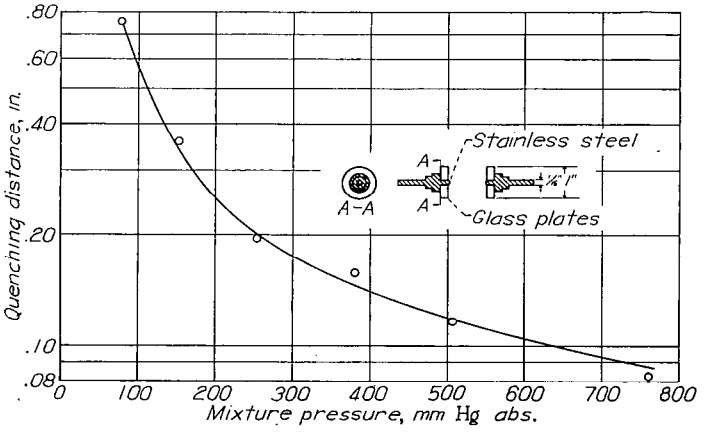
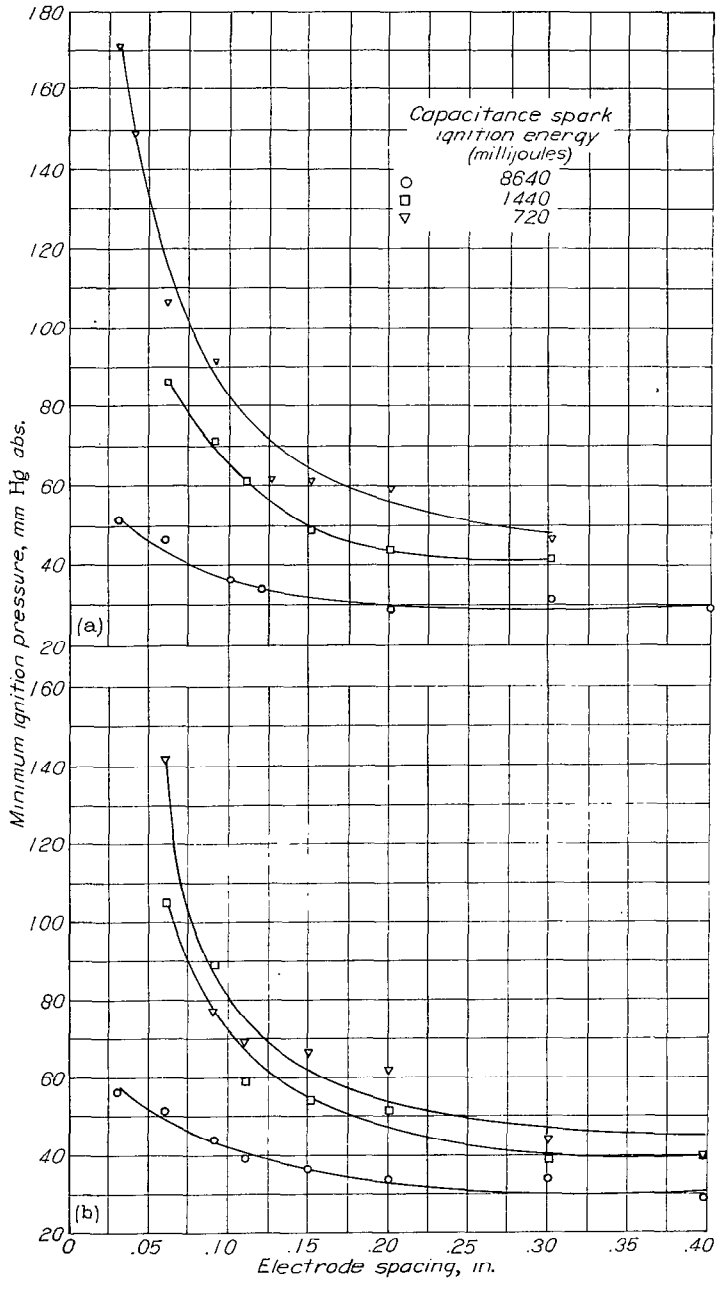


FIGURE 36.—Effect of mixture pressure of 8.5 to 9.5 percent by volume mixture of methane and air at temperature of 77° F on quenching distance of one electrode configuration. (Data from reference 50.)

meters of mercury absolute for a 1.75 percent by volume mixture of gasoline in air. The lower and upper limits of inflammability of 100-octane gasoline and air mixtures are relatively unaffected by mixture pressure changes above 60 and 300 millimeters of mercury absolute, respectively.



(a) *n*-Butane, 3.5 percent by volume.

(b) 2,2,4-Trimethylpentane, 2.5 percent by volume.

FIGURE 37.—Effect of electrode spacing on minimum ignition pressures of two fuel-air mixtures at temperatures of 70° to 75° F. Ignition by spark-plug-electrode configuration in 2-inch inside-diameter by 3½-inch glass reactor. (Data from reference 58.)

The effect of pressure on the quenching distances or electrode spacings of various electrode configurations producing incendiary sparks is shown in figures 36 and 37. For constant spark-ignition energies, the quenching distances, or electrode spacings, of incendiary-spark-producing electrode configurations increase with decreasing inflammable mixture pressures. This phenomenon is explained by assuming that a constant spark-ignition energy can initially ignite a constant mass of inflammable mixture. Thus, with decreasing mixture pressure, ignition of a larger volume of inflammable mixture occurs, and the electrode spacing must be increased to accommodate the increased mixture volume.

Variation of minimum spark-ignition energy with mixture pressure is expressed in figures 38 to 40. For constant electrode spacing, the minimum spark-ignition energy of a mixture increases with decreasing mixture pressure. The minimum spark-ignition energies of inflammable mixtures increase rapidly near the minimum ignition pressures of the mixtures (fig. 40).

Varying temperature.—Varying the temperature of inflammable mixtures from −50° to 300° F has a small effect on the minimum ignition pressures of the mixtures when ignition is initiated by high-energy capacitance sparks. As indicated in figure 41, the minimum ignition pressures of *n*-butane–air and isooctane-air mixtures decrease linearly with increasing mixture temperatures when ignition is effected by capacitance sparks having spark-ignition energies from 720 to 8640 millijoules. The minimum ignition pressures of *n*-butane–air and isooctane-air mixtures are approximately the same regardless of the spark-ignition energies at mixture temperatures of 300° F.

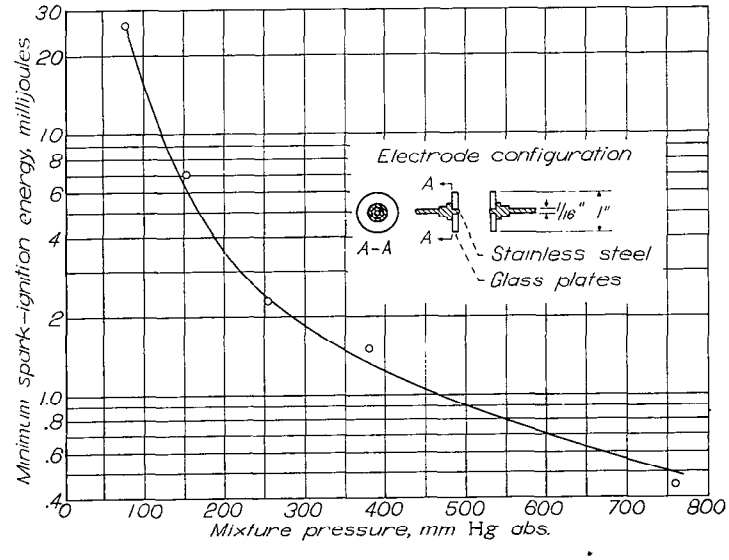


FIGURE 38.—Effect of pressure of 8.5 to 9.5 percent by volume mixture of methane and air at temperature of 77° F on minimum spark-ignition energy for one electrode configuration. (Data from reference 50.)

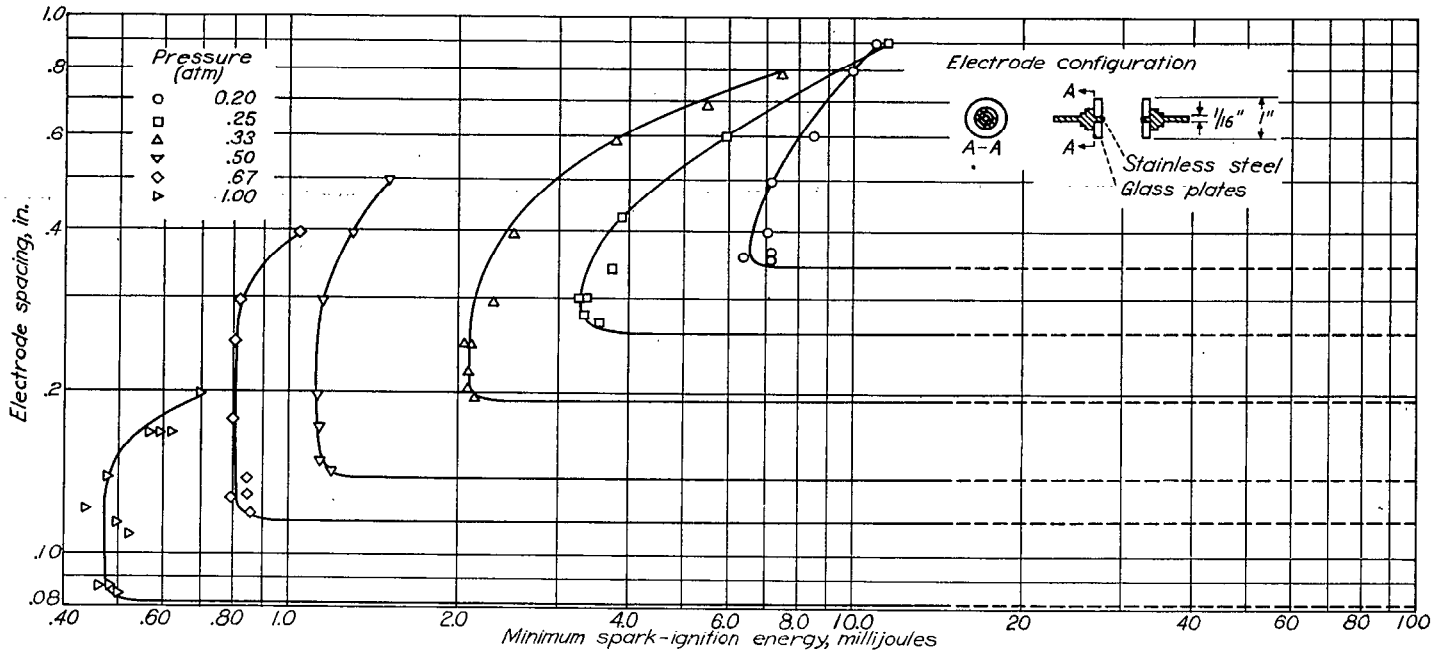


FIGURE 39.—Minimum spark-ignition energy of glass-flanged electrode configurations as functions of electrode spacing and pressure of 9.5 percent by volume mixture of methane and air at temperature of 77° F. (Data from reference 50.)

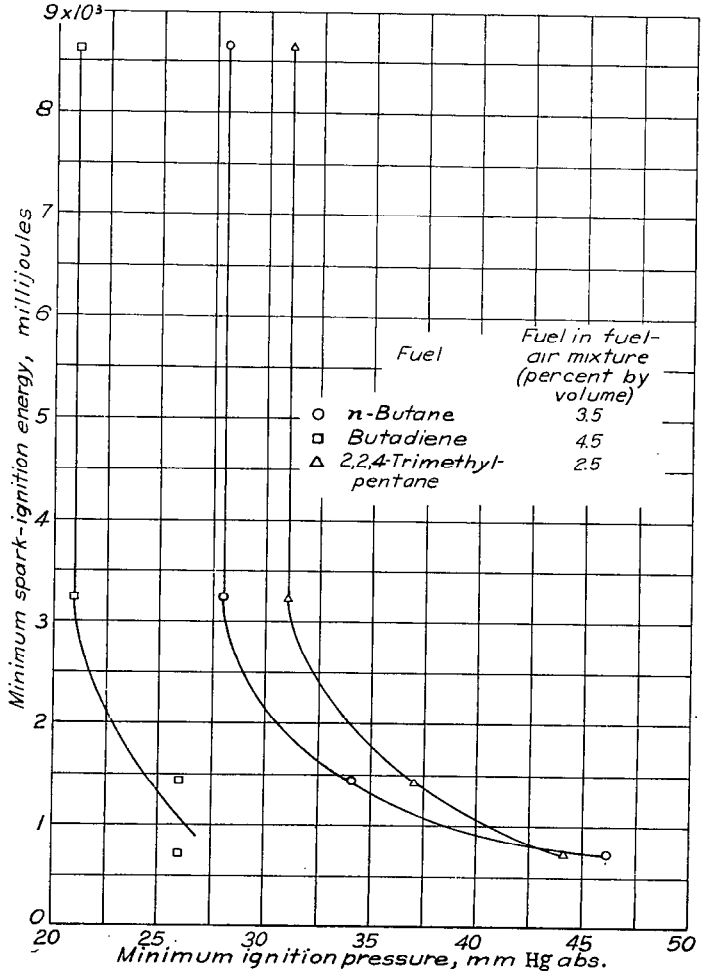
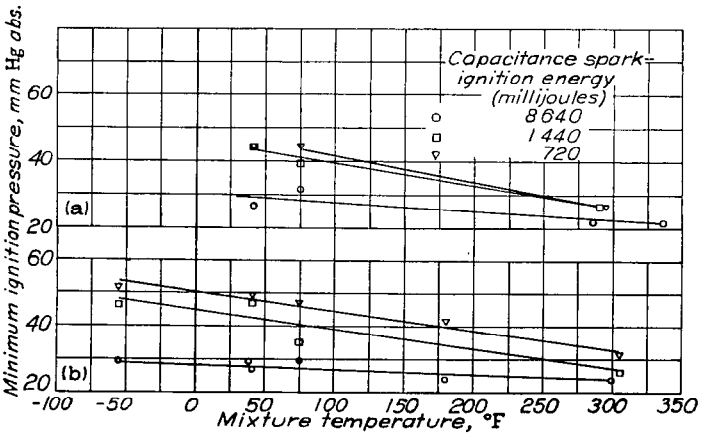


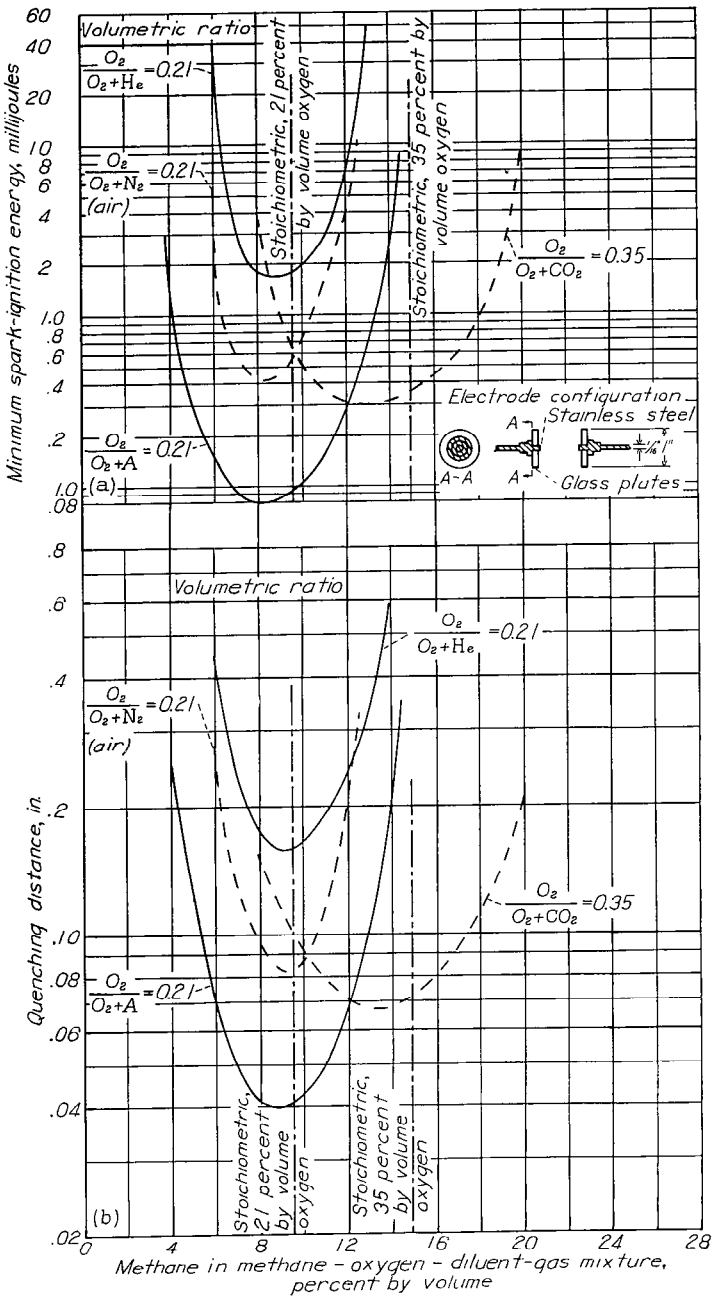
FIGURE 40.—Effect of mixture pressures on minimum spark-ignition energy of one electrode configuration. Electrode spacing, 0.110 inch; capacitance-spark voltage, 600 volts. All mixtures slightly richer than stoichiometric. (Data from reference 58.)



(a) 2,2,4-Trimethylpentane in air, 2.5 percent by volume.

(b) *n*-Butane in air, 3.5 percent by volume.

FIGURE 41.—Effect of mixture temperature on minimum spark-ignition pressures of 2,2,4-trimethylpentane and *n*-butane-air mixtures. Method of ignition, bomb; electrode configuration, spark-plug; electrode spacing, 0.110 inch; volume of bomb, 750-cubic-centimeters. (Data from reference 58.)



(a) Minimum spark-ignition energy.
(b) Quenching distance.

FIGURE 42.—Effect of diluent-gas addition on minimum spark-ignition energy and quenching distance of methane–oxygen–diluent-gas mixtures at temperature of 77° F and pressure of 1 atmosphere. (Data from reference 50.)

EFFECT OF DILUENTS

The presence of diluent gases in an inflammable mixture exerts a significant influence on its electric spark ignition. Like heated surface ignition, the spark-ignition energy required to ignite inflammable mixtures containing large percentages of diluents depends on the absorptive and conductive powers of the diluents and the proportion of inflammable gas to oxygen. Figure 42 indicates the effect of diluents on the minimum spark-ignition energies and quenching distances of methane–oxygen–diluent-gas mixtures. In figures 42 (a) and 42 (b), the relative effect of the diluent gases is the same. With the exception of the methane-oxygen-argon mixtures, the minimum ignition energies and quenching distances increase with increasing diffusivity of the oxygen–

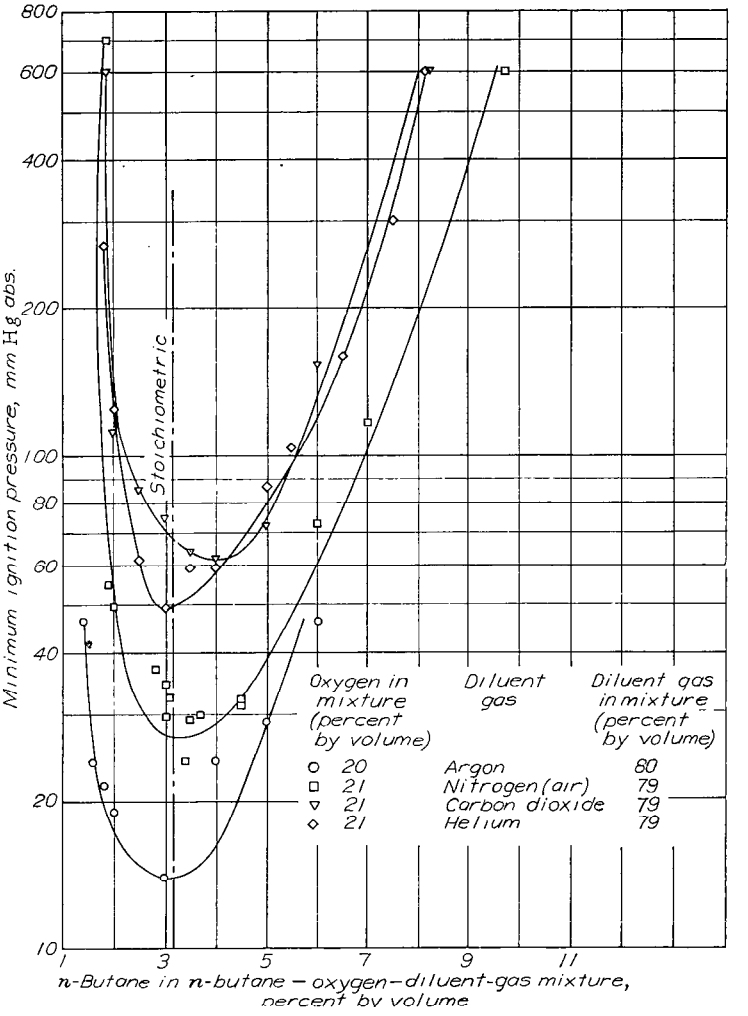


FIGURE 43.—Effect of diluent-gas addition on minimum ignition pressures of *n*-butane–oxygen–diluent-gas mixtures. Method of ignition, bomb; electrode spacing, 0.110 inch; capacitance-spark ignition energy, 8640 millijoules; volume of betal bomb, 750 cubic centimeters; mixture temperature, 74° to 82° F. (Data from reference 58.)

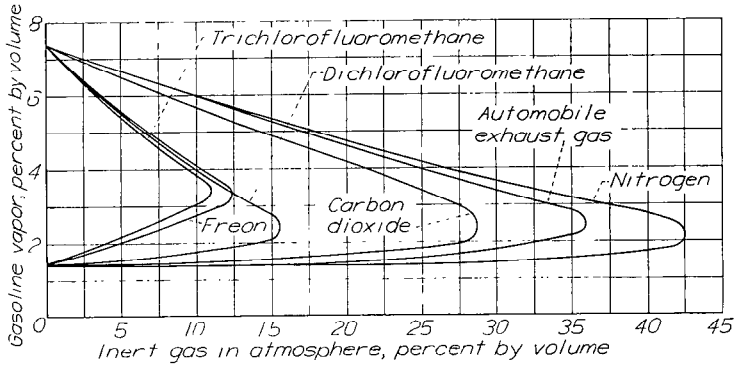


FIGURE 44.—Limits of inflammability of gasoline vapor in various air—diluent-gas atmospheres. Automobile-exhaust-gas composition: nitrogen, 85 percent by volume; carbon dioxide, 15 percent by volume. Gasolines tested: 73, 92, and 100 octane. Inflammable area covers entire area inside largest curve. (Data from reference 61.)

diluent-gas mixtures. This mixture diffusivity is expressed by

$$\alpha = \frac{k}{\rho c_p} \tag{6}$$

where

c_p mixture specific heat
k mixture thermal conductivity
α mixture thermal diffusivity
ρ mixture density

The minimum ignition pressures of mixtures of *n*-butane and oxygen, with argon, nitrogen, carbon dioxide, and helium as diluents are shown in figure 43. For all the inflammable mixtures containing diluents, the mixtures most and least ignitible are those containing argon and carbon dioxide, respectively. The effect of several diluents on the limits of inflammability of individual mixtures of 73-, 92-, and 100-octane gasoline and air is shown to be identical in figure 44. The lower limit of inflammability of the mixture is relatively unaffected, whereas the upper limit decreases approximately linearly with increasing amounts of diluents such as carbon dioxide, automobile exhaust gas, and nitrogen. Mixtures of 100-octane gasoline and air are rendered noninflammable by the addition of approximately 28.7, 36.0, and 42.5 percent by volume of carbon dioxide, automobile exhaust gas, or nitrogen, respectively. Halogenated hydrocarbons are more effective than any of these diluents in rendering gasoline-air mixtures noninflammable.

III—IGNITION BY FLAMES OR HOT GASES

Data pertaining to the ignition of inflammable mixtures by flames or hot gases are not extensive. Much of the available data pertain to the ignition of gas-air mixtures containing methane as the chief inflammable constituent. Whether the inflammable mixtures will or will not be ignited by flames or hot gases depends on mixture composition, duration of contact of the mixture with the ignition source, temperature of the ignition source, and size of the ignition source, in much the same manner as ignition by heated surfaces.

EFFECT OF VARYING MIXTURE COMPOSITION

The effect of mixture composition on the limiting diameters of openings for downward propagation of flames in methane-air mixtures is shown in figure 45. Limiting diameters occur with approximately stoichiometric compositions. The ignition of an inflammable mixture by a flame can be considered practically instantaneous. Methane-air mixtures exposed to flames 0.394, 0.492, and 0.591 inch in length exhibited ignition lags of 0.0068, 0.0042, and 0.0035 second, respectively; therefore, even though the ignition lag is practically zero for flame ignition, the lag decreases with increasing size of the ignition source. Minimum ignition lags have been found to occur with approximately stoichiometric mixtures.

LIMITING SIZE OF OPENINGS FOR FLAME PROPAGATION

The minimum quenching distances or the limiting diameters of tubes or holes in thin plates through which a flame will not propagate are expressed in figures 45 to 47. Minimum limiting tube and thin plate opening diameters of approximately 0.071 and 0.136 to 0.150 inch occurred for approximately stoichiometric mixtures of coal gas and methane with air, respectively. These limiting diameters for the downward propagation of flame in inflammable mixtures were determined for copper tubes having length-diameter ratios l/d of 10, and for circular openings in thin copper foil and mica plates having thicknesses of 0.0033 inch and 0.0024 to 0.0087 inch, respectively.

Some references (for example, references 62 and 67) indicate that the quenching of the flame is due solely to the cooling effect of the unburned gases rather than a cooling effect due to varying thermal conductivity of the confining material. Data from reference 68 indicate that in addition to this effect the confining material and opening configuration may affect the quenching distance by varying the size of the dead space between the surface of the flame and the opening of the enclosure. The reduced inflammability range and the increased limiting diameter of opening for downward flame propagation determined with copper tubes instead of openings in copper foil may be due to an increase in the size of the dead space caused by the greater over-all cooling effect of the copper tubes. Investigations conducted with the glass tubes and the mica plates (references 62 and 63) gave approximately the same results as experiments in which copper tubes and plates were used.

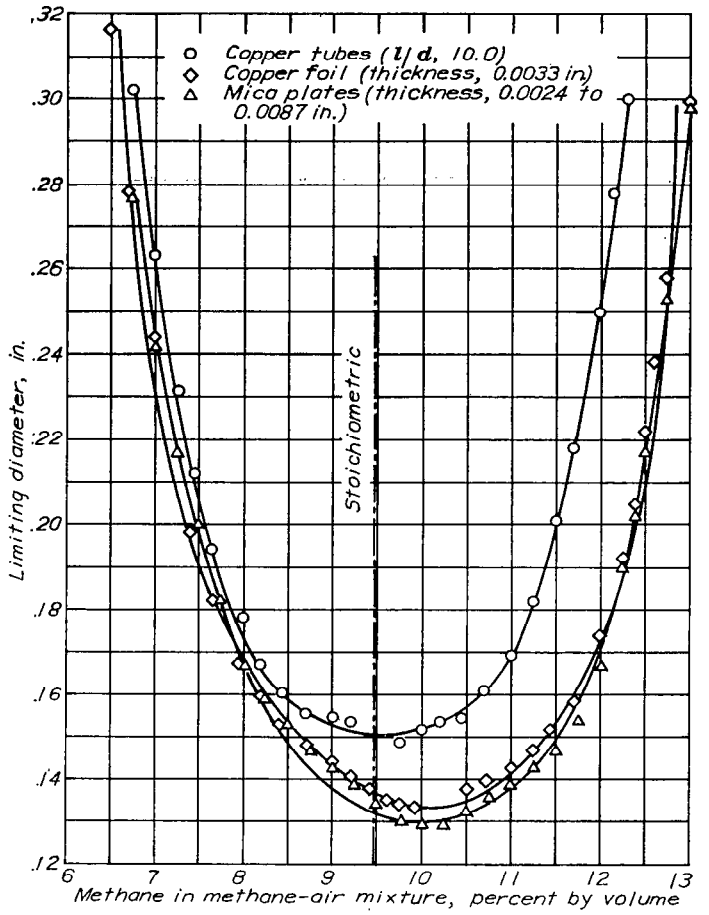


FIGURE 45.—Effect of mixture composition on limiting diameters of openings in copper and mica plates and copper tubes for downward flame propagation in methane-air mixtures at atmospheric pressure. (Data from reference 62.)

No data were found in the survey of the literature to indicate the limiting sizes of openings for propagation of flames of gasoline-air mixtures. Reference 65, however, indicates that the quenching of laminar oxyhydrogen flames by solid surfaces is partly dependent on the factor k/SC, where

C heat capacity per unit volume of unburned mixture at quenching temperature
k thermal conductivity of unburned mixture at quenching temperature
S burning velocity of mixture

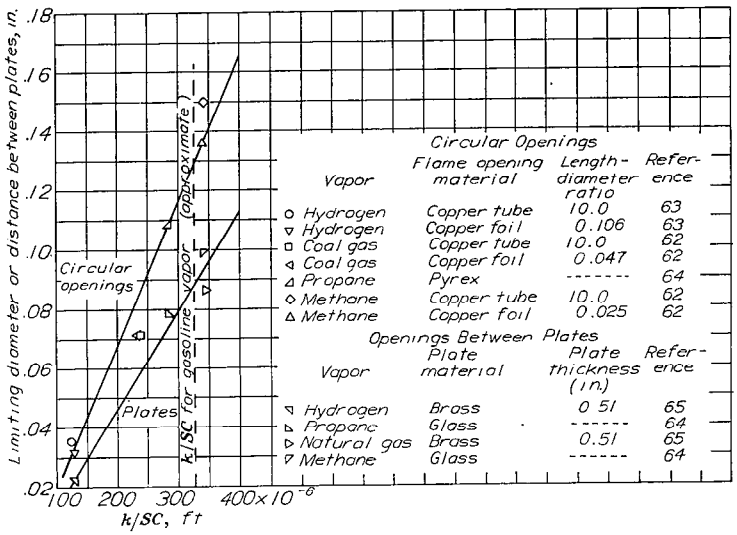


FIGURE 46.—Limiting diameters of circular openings and limiting distances between plates for downward propagation of flame in various vapor-air mixtures at atmospheric pressure.

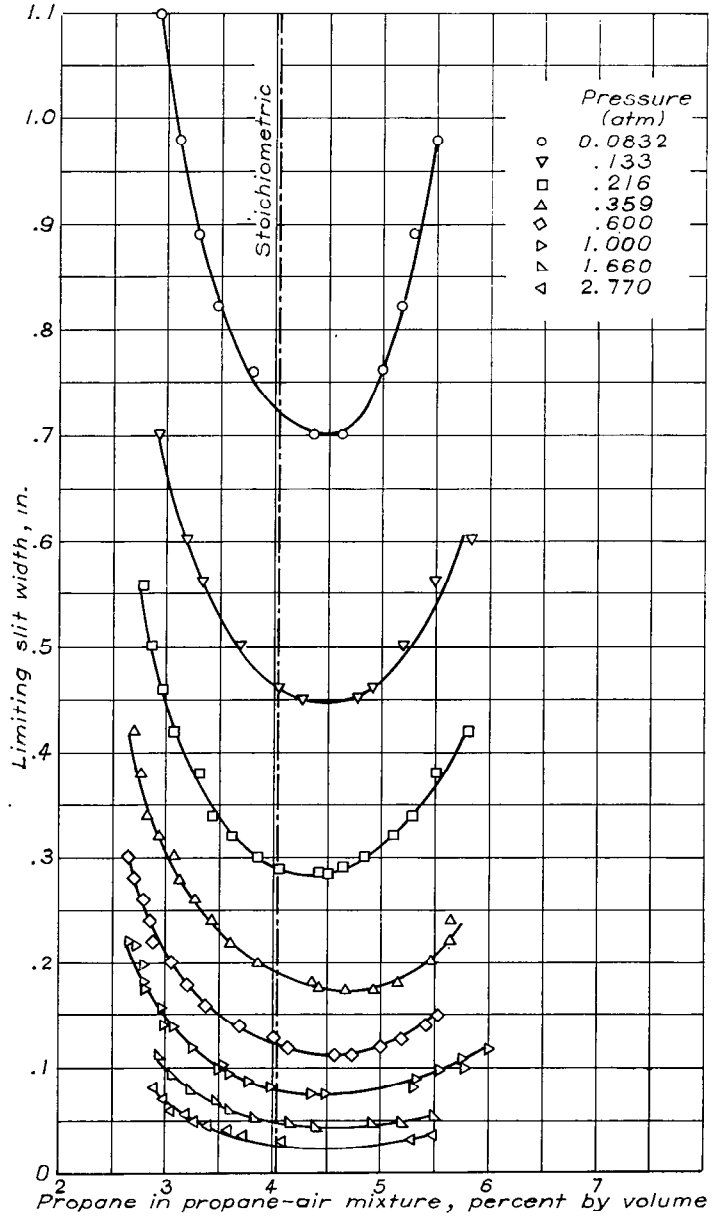


FIGURE 47.—Quenching of propane-air flames at various mixture pressures and temperature of 75° F; downward flame propagation. (Data from reference 66.)

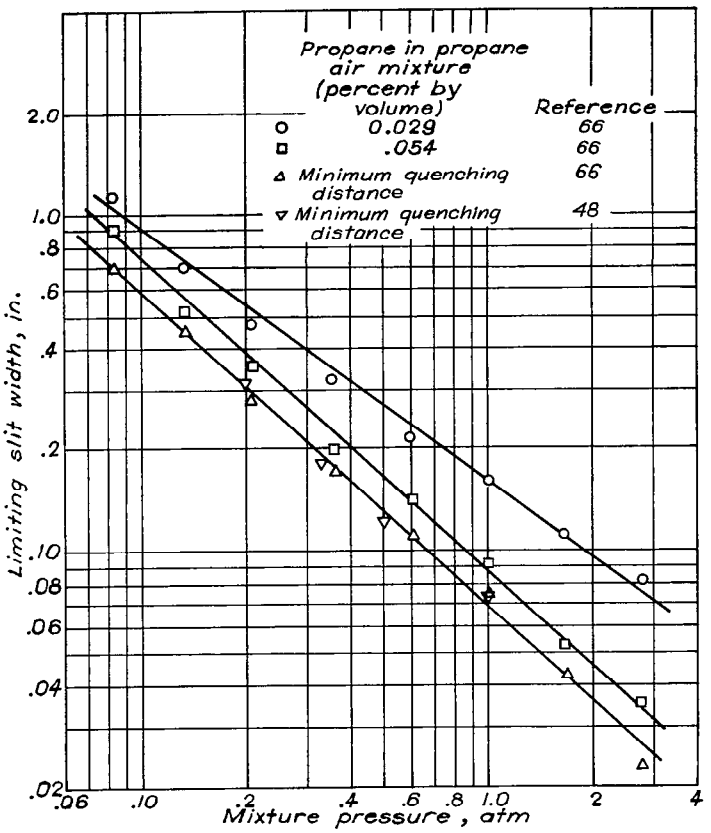


FIGURE 48.—Quenching of propane-air flames at various mixture pressures and temperature of 75° F. Downward-flame-propagation data, reference 66; spark-ignition data, reference 48.

Figure 46 was plotted, using values of k/SC calculated as indicated by reference 65. Experimental data, which pertain to the limiting size of openings for flame propagation in gasoline-air mixtures, are unavailable in the literature. Accordingly, k/SC was calculated for a stoichiometric n-octane–air mixture, which was assumed to be approximately the same as a stoichiometric gasoline-air mixture. This calculated value of k/SC indicates (fig. 46) that the limiting diameter of circular openings and the limiting distance between parallel plates for downward flame propagation in gasoline-air mixtures are approximately 0.13 and 0.09 inch, respectively.

EFFECT OF GAS PRESSURES AND TEMPERATURES

The effect of mixture pressure on the quenching of propane-air flames is indicated in figure 47. The configuration used consisted of a rectangular opening in $\frac{3}{16}$-inch copper plates. The length-width ratio of the slit was always greater than 3.6. For all mixture pressures from 0.0832 to 2.77 atmospheres, the minimum limiting slit width for downward propagation of flame occurs with mixtures slightly richer than stoichiometric. As shown by figure 48, for any single mixture composition, the dependency of the limiting slit width on the mixture pressure is expressed approximately

by an equation of the form

$$w = Kp^n \qquad (7)$$

where

K constant
n negative exponent
p mixture pressure
w slit width

The results of investigations conducted with propane-air flames at atmospheric pressure to determine the effect of mixture temperature on the limiting slit width of the quenching configuration just described are presented in figure 49. The mixture and the plates forming the rectangular opening were at the same temperature. For all temperatures from 80° to 545° F, the minimum limiting slit width occurs with mixtures slightly richer than stoichiometric. The limiting slit width decreases with increasing mixture temperature. Similar data for brass-plate protective devices in natural-

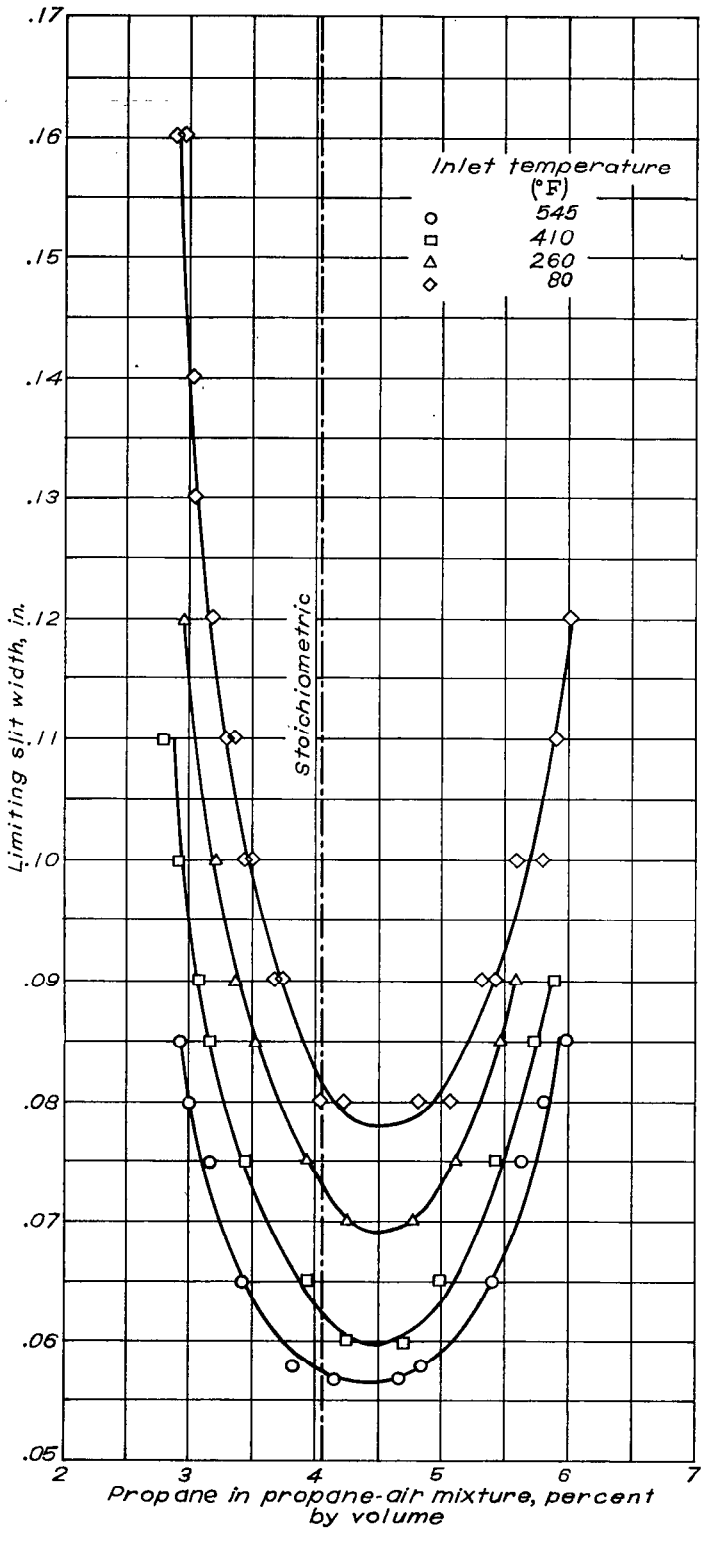


FIGURE 49.—Quenching of propane-air flames at various mixture temperatures (gas and plates at same temperature). Pressure, 14.3 pounds per square inch absolute; slit length-width ratio, > 3.6; slit jaws, 3/16-inch copper plates; downward flame propagation. (Data from reference 66.)

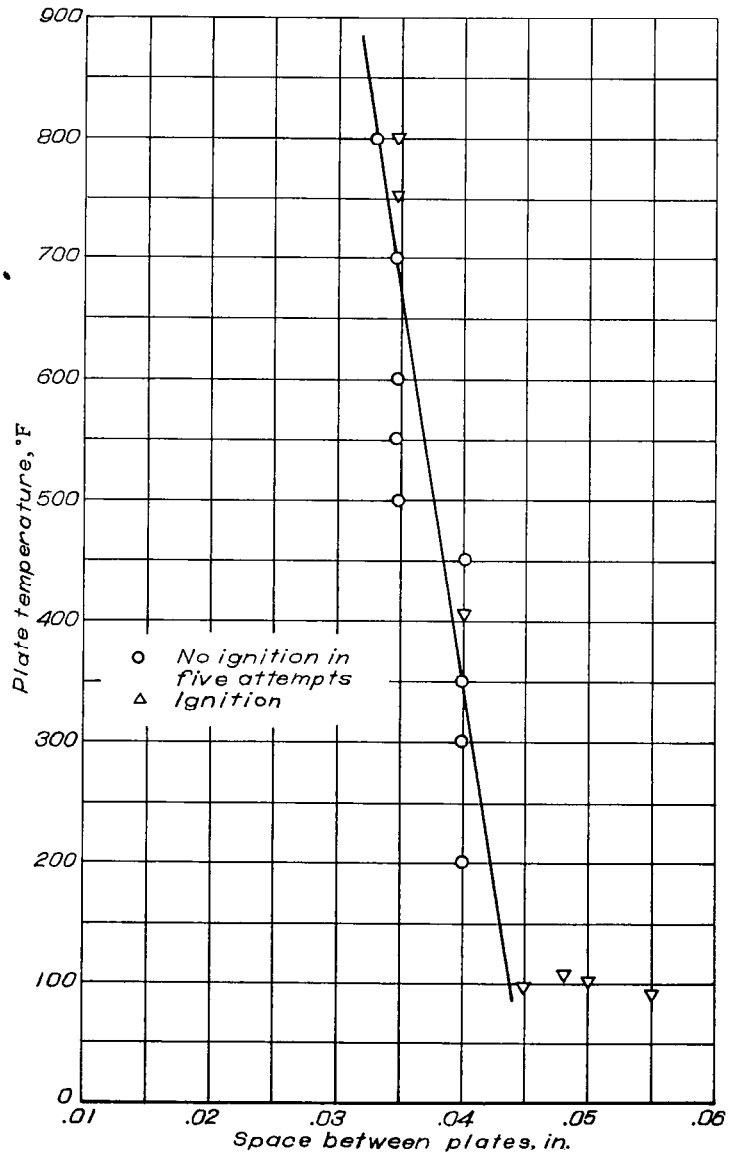


FIGURE 50.—Effect of plate temperature on performance of brass-plate protective device (plates, 0.09 in. by 4 in.) in inflammable atmospheres containing 8.6 to 9.5 percent by volume natural gas in air. (Data from reference 69.)

gas–air atmospheres are given in figure 50. The limiting distance between plates for a single mixture decreases linearly with increasing plate temperature.

EFFECT OF DILUENTS

The effect of diluents on the limiting diameter of openings for propagation of flames in methane-oxygen-nitrogen (air) and methane-oxygen-argon mixtures is shown in figure 51. The minimum limiting diameters of copper tubes (length-diameter ratio = 10.0) are 0.150 and 0.087 inch, respectively, for flame propagation in the methane-air and methane-oxygen-argon mixtures. The cooling effect of the unburned gases is indicated by the smaller limiting diameters of openings for flame propagation in mixtures having the smaller heat capacities and thermal conductivities.

IV—RELATION OF PUBLISHED DATA TO AIRCRAFT-FIRE PROBLEMS

Fires in aircraft usually result from the ignition of inflammable vapors by heated surfaces, hot (electric) sparks and arcs, and flames or hot gases. The source of ignition can often be definitely determined for fires during flight or ground operation of aircraft, but the ignition source in crashes is often unknown, because the inflammables may sometimes be exposed to all the ignition sources simultaneously.

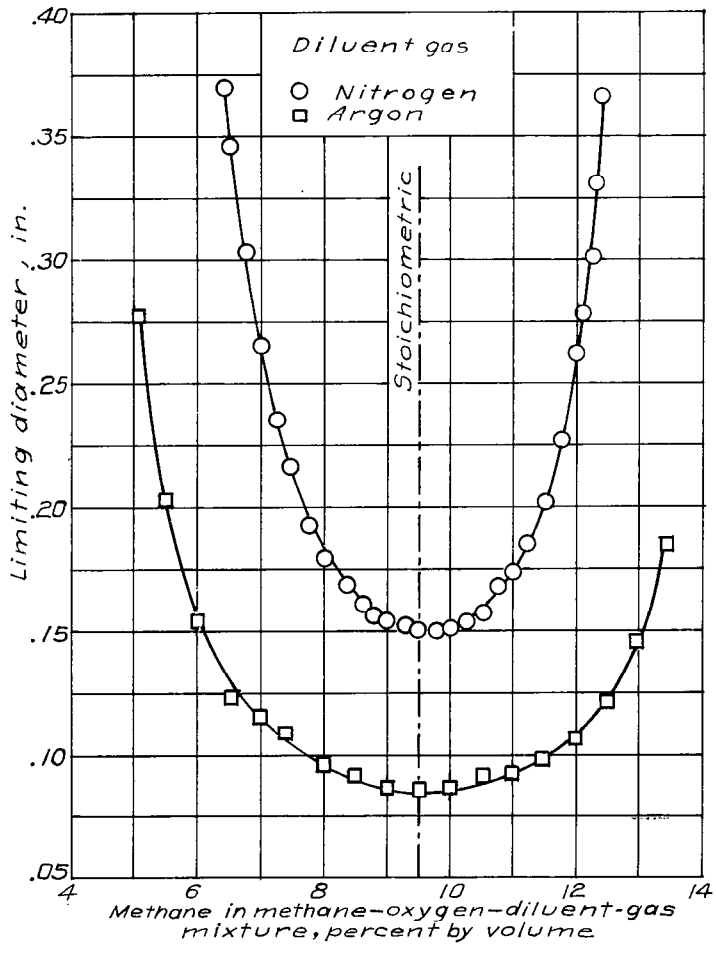


FIGURE 51.—Effect of diluent-gas additions on limiting diameters of openings for flame propagation in methane-oxygen-diluent-gas mixtures. Downward flame propagation through copper tubes; length-diameter ratio, 10.0; ratio of oxygen to diluent, 21:79. (Data from reference 63).

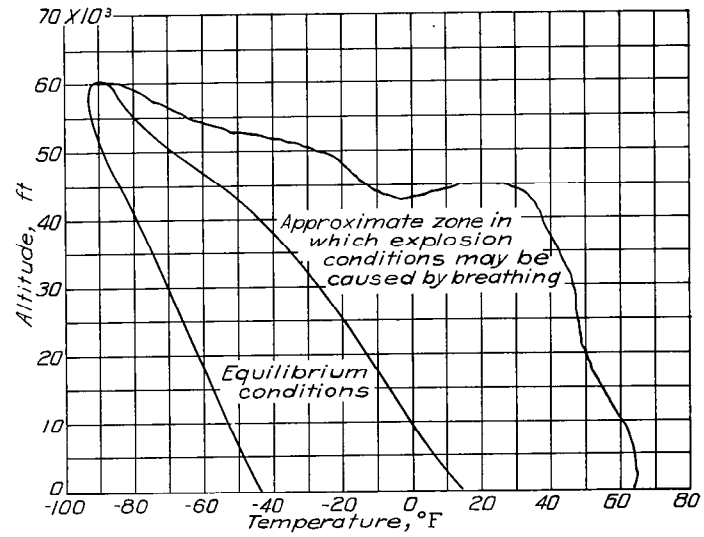
IGNITION BY HEATED SURFACES

Heated surfaces are common ignition hazards in aircraft environments. According to reference 70, hot exhaust ducts, combustion heaters, carburetor-air heaters, overheated cabin superchargers, moving parts overheated by friction, and short circuited or malfunctioning electric equipment have been responsible for the heated surface ignition of fires in airline aircraft in the decade prior to 1947. Of these surface-ignition hazards, the exhaust system is a continuous hazard during operation of the aircraft. The other ignition sources exist intermittently, generally because of malfunctioning or mechanical failure of the particular component.

A survey of air-transport crash records (reference 71) indicates that the inflammable most frequently initially involved in flight or ground fires and thus considered most hazardous of the liquids carried in aircraft is gasoline. Lubricating oil is not quite as hazardous as gasoline because of its much higher flash point and much lower volatility. Half the fires mentioned in the survey of flight fires involved either gasoline or lubricating oil as the initial inflammable.

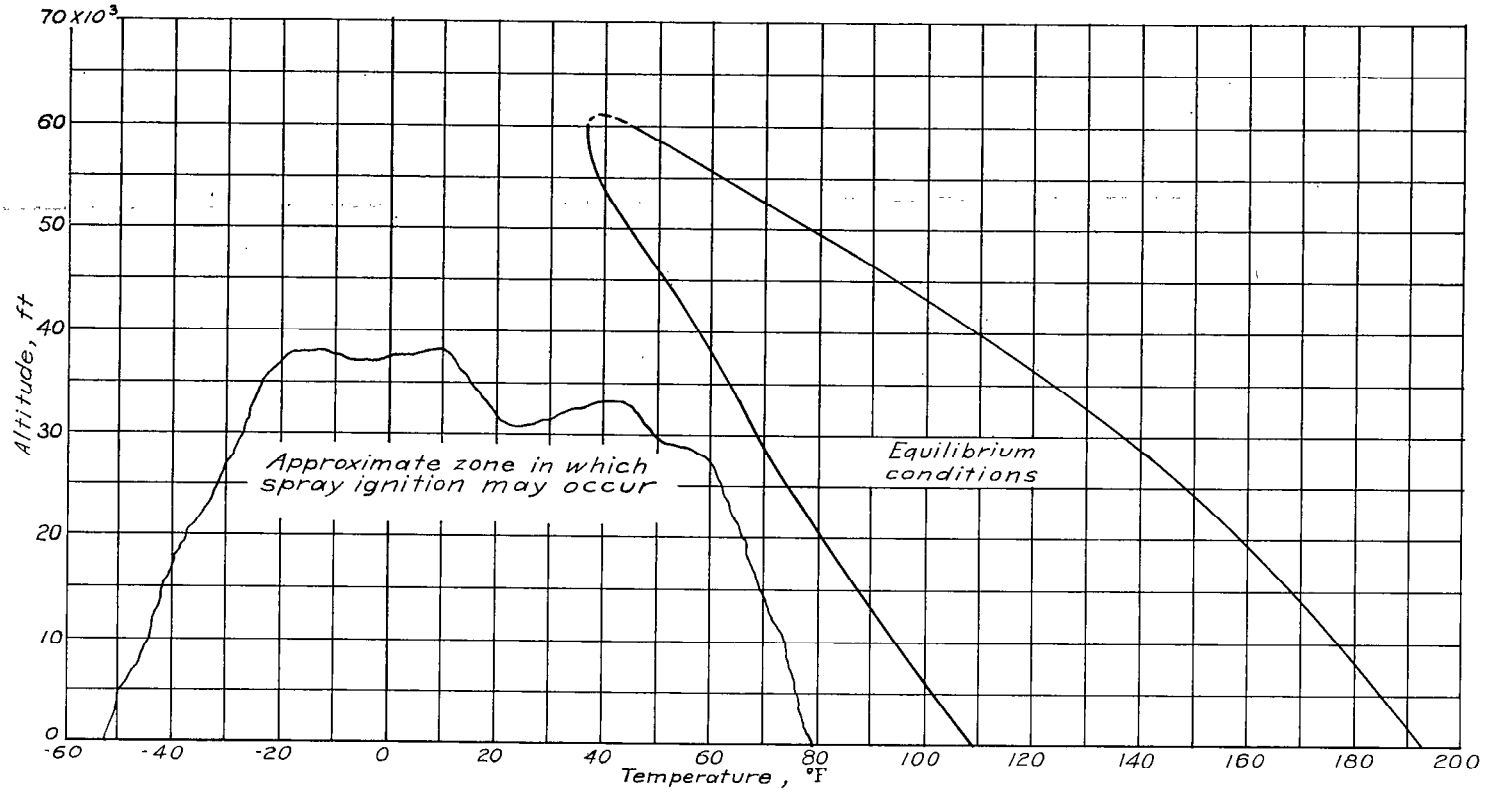
In order to ignite any inflammable by a heated surface, the right proportions of the inflammable must contact the heated element. The temperature at which ignition occurs depends on the length of time the inflammable is in contact with the heated air or surface. According to the aforementioned survey, this contact is brought about during ground operation mainly by failure of the fuel plumbing system. Typical of fuel-plumbing-system failures are primer line failures, primer leaks, leaky hose connections, fuel pump leakage, and failure of the carburetor vent line. Serious accessory section fires in radial engines are often due to this type of failure, which allows inflammable vapors or fluids to escape and contact or drop on the hot exhaust stacks.

Flight fires are due primarily to engine failures, which usually are the result of structural faults of various components. Engine failures, especially in radial engines, often result in a rupture of the engine induction and exhaust systems. This type of failure can easily be brought about by engine cylinders displaced by broken connecting rods. When



(a) Fuel, 100-octane gasoline.

FIGURE 52.—Zones of inflammability of fuel in aircraft fuel tanks. (Data from reference 72.)



(b) Fuel, kerosene.

FIGURE 52.—Zones of inflammability of fuel in aircraft fuel tanks. (Data from reference 72.)

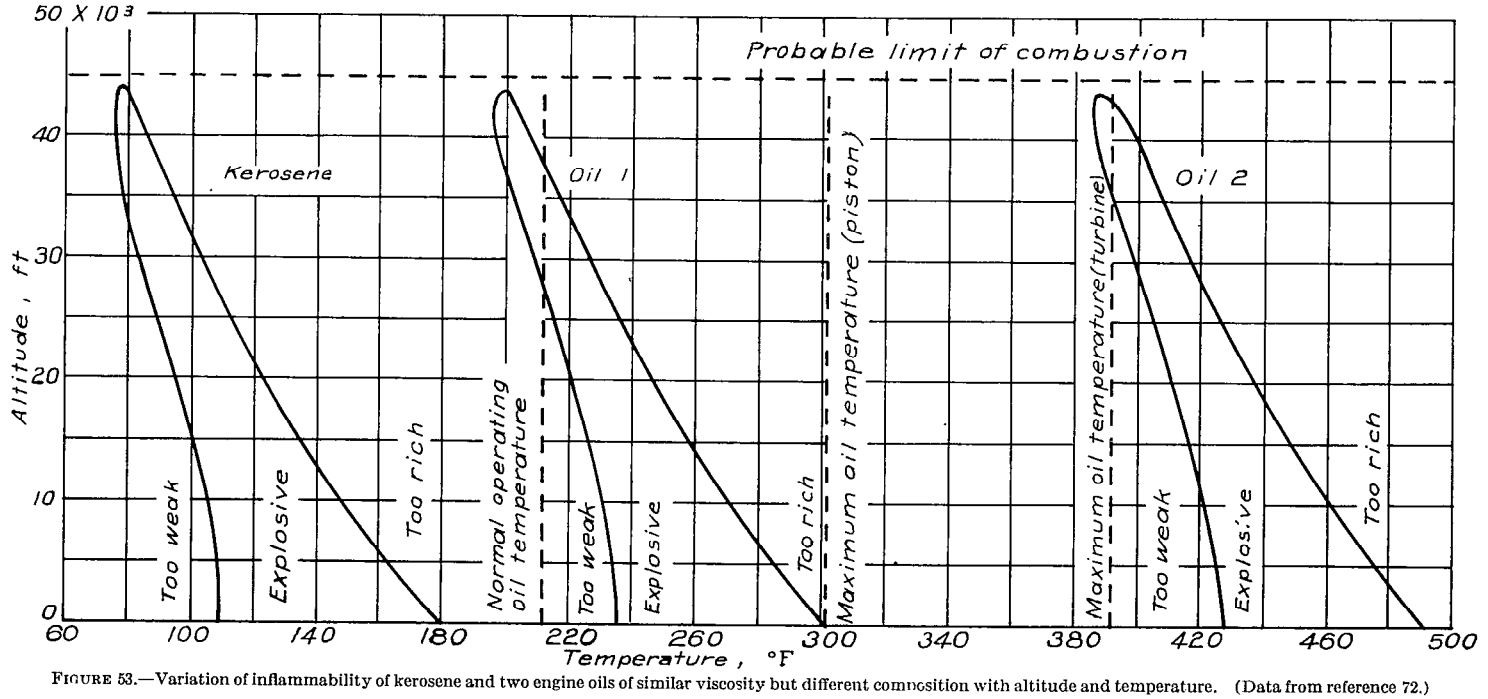


FIGURE 53.—Variation of inflammability of kerosene and two engine oils of similar viscosity but different composition with altitude and temperature. (Data from reference 72.)

such a displacement occurs, inflammable fuel-air mixtures and hot lubricating oil are exposed to hot surfaces, which are primarily components of the exhaust system. Usually, it is difficult to state whether inflammation results from ignition of the gasoline or the lubricating oil. Crash fires are generally due to structural failure of the engine, but are much more severe than flight fires in most cases.

In the range of its ignition temperatures (450° to 1325° F), gasoline can exist only in the vapor state. Any mixture capable of flame propagation must lie within the limits of inflammability. According to figure 52, aircraft fuel-tank minimum temperatures of −44° and 108° F are explosively dangerous at sea level for 100-octane aviation gasoline and kerosene, respectively. The area marked "equilibrium conditions" indicates the limiting conditions at which inflammable mixtures exist in the fuel tank in equilibrium with the fuel. Breathing, which widens the limiting conditions for gasoline, is the influx of air into a fuel tank during a descent

due to increasing atmospheric pressure. For kerosene, which has a flash point generally greater than ambient temperatures, the ignition zone is widened by conditions under which an ignitible spray may be formed. Research carried out since the publication of figure 52 (b) has shown that the zone in which spray ignition of kerosene may occur is known to be larger than reference 72 indicates. A fuel mist or spray may be formed by the rupture of a fuel tank by a missile or the rupture of a high pressure fuel line such as are present in turbojet engines. Similar data are plotted in figure 53 for kerosene and for two lubricating oils of different composition but of the same viscosity.

In any occurrence of these fire hazards in aircraft, the ignition temperature and ignitibility of the fuel or lubricating oil will be determined by conditions described in the detailed discussion presented herein. The values of ignition temperature and ignitibility defined by these conditions serve as approximate indications of the relative temperatures at which heated surfaces become practical hazards in aircraft environments. Reference 12 indicates that aviation gasoline will not ignite in air when exposed to the outer surfaces of exhaust pipes at temperatures below 850° F. Injected into air inside hot exhaust pipes, aviation gasoline ignited at duct temperatures as low as 536° F. Lubricating oil on the outer surfaces of exhaust ducts ignited at a minimum duct temperature of 625° F. Thus, for complete immunity to fires ignited by the components of the exhaust system, the surface temperatures should not be greater than approximately 500° F. Although existing knowledge does not permit a complete description of the components of the exhaust system that serve as ignition sources, it is presumed in this discussion that the exhaust duct, the exhaust valves, and the cylinder interiors are the active components.

Volatile fuels necessary for engine operation under a variety of climatic conditions may be responsible for the relative ignition hazard of present-day grades of gasoline used in aircraft operation. As the volatility of a fuel increases, the range in which ignition sources are hazardous increases. Fuels of low volatility would result in more difficult starting of aircraft engines, but would seemingly reduce the ignition hazard of fuel in aircraft environments.

Reduction of the fire hazard of the exhaust system can be accomplished by:

(1) Keeping the inflammables from the hot surfaces

(2) Releasing some substance into and around the exhaust system in order to prevent ignition if a crash is imminent

(3) Cooling the exhaust system below temperatures capable of ignition of gasoline or oil

(4) Increasing the minimum ignition temperature of the fuel or oil by changing the fuel or oil composition or by change of material used in the construction of the exhaust ducts

(5) Changing the volatility of the fuel.

An extinguishing system capable of spraying or flooding the exhaust ducts would aid in preventing combustion by simultaneously blanketing and lowering the temperature of the heated surfaces. According to reference 73, "it is most important that the extinguishant should be actually injected into enclosed hot spaces such as exhaust ducts, long exhaust pipes or collector rings, turbine compartments and tailpipe ducts, and combination heater chambers."

The ignition temperature of gasoline is increased by the addition of small amounts of tetraethyl lead, benzene, and similar substances. Possibly other substances can be found that will increase the ignition temperature without reducing the performance of the fuel in the engine.

Changes in the surface composition of the exhaust-duct material may effectively increase the ignition temperature of the fuel. Dependent upon the mixture composition, highly catalytic surfaces such as platinum must be heated to temperatures 300° to 700° F greater than stainless steel to ignite inflammable mixtures. Use of platinum is obviated by its cost and therefore the aforementioned comments are only of academic interest.

Fuel-volatility changes apparently are desirable relative to the fire-hazard problem. According to tables III and IV, the surface-ignition temperatures of low-volatility safety fuels do not vary greatly from those of regular grades of aviation gasoline. Reduced fuel volatility would not increase the ignition temperature of the fuel, but would reduce the volume in which an ignition source is hazardous.

IGNITION BY ELECTRIC SPARKS AND ARCS

Sparks resulting from short circuits in wiring or from failures of starters, magnetos, or generators; sparks from the continued functioning of nonflameproofed electric apparatus; sparks from the continued rotation of damaged parts; discharges from the brushes of rotating equipment; sparks from ground friction; electrostatic sparks; and electric arcs created by the separation of metallic contacting portions of the electric circuit such as voltage regulators may all be regarded as potential spark-ignition hazards in aircraft.

Flight fires in transport aircraft are initiated with equal frequency by either electric sparks or the exhaust ducts (reference 71). The damage incurred by the electric spark-ignited fires, however, was generally confined to the electric insulation. In addition, reference 74 shows that self-clearing arcs are statistically more prevalent during the breaking of a load-carrying circuit. The clearing time was from 0.05 to 2.5 seconds, with a median value of 0.6 second. Compared with the exhaust system, electric sparks are relatively short, minor ignition hazards during flight operation.

High-energy concentrations at short-circuited points result in self-clearing faults, but are generally accompanied by a scattering of molten metal globules over a considerable area. Low-energy concentrations at short-circuited points may result in a permanent welded contact between the conductor and the airplane structure. Self-clearing faults are probably more dangerous than welded faults because they are accompanied by extremely high temperatures and considerable arcing. Welded faults, however, may disrupt the entire electric system and thus interfere with control of the airplane.

Continued rotation of generators is generally not significant in propeller-type aircraft in the event of crash. In jet-type aircraft, free running turbines may, however, continue rotation of such parts.

According to the survey (reference 71) of fires in transport aircraft, two of the 61 crash fires reported were initiated by sliding friction. Inasmuch as data indicate that friction sparks ordinarily lack the thermal energy capable of igniting

inflammable mixtures, the source of ignition of these two crash fires may have been surfaces heated to high temperatures by sliding friction rather than by friction sparks.

Electrostatic sparks generated in aircraft environments may be ignition hazards. Electrostatic charges having potentials of 50 to 2000 volts have been accumulated in air of 30- to 51-percent humdity at atmospheric pressure and temperature by benzene flowing through a 0.12-inch tube into an insulated receiver. The following table from reference 75 indicates the potentials of electrostatic charges accumulated in air of 63-percent humidity at atmospheric conditions by benzene flowing through tubes of different materials.

Tube material	Potential of accumulated charge (volts)
Iron	4000
Brass	3600
Aluminum	2900
Copper	2000

In air of 78-percent humidity, no charge was accumulated when the benzene flowed under its own pressure, but even a slight increase in the liquid pressure resulted in an accumulation of a high-potential electrostatic charge. At liquid pressures of 2 to 6 atmospheres, electrostatic charges having potentials of 4000 volts and greater were accumulated. Thus, unless the equipment is suitably grounded, practically any transfer of fuel in any environment is hazardous.

According to reference 76, the potential of the electrostatic charge accumulated during fuel transference is approximately the same for any grade of gasoline or kerosene, increases with the length of time of the transferring operation, increases with increasing fuel velocity, and is relatively unaffected by atmospheric conditions except that it decreases with increasing humidity of the air.

The capacitance of the human body has been determined (reference 77) as 0.0001 to 0.0004 microfarad. Values of 0.00028 to 0.00032 microfarad were consistently obtained for the capacitance of a person leaning against a wall. An individual charged to a potential of 10,000 volts would have an electrostatic spark energy of 15 millijoules. Because many inflammable mixtures have minimum spark-ignition energies less than 15 millijoules, and this amount of electrostatic spark energy is easily acquired by ungrounded personnel, equipment, and wiring, grounding precautions should be taken.

Most of the sparks occurring in aircraft environments ordinarily contain many times the energy required to ignite inflammable mixtures. Sparks of this type must be prevented from occurring in an inflammable atmosphere. According to reference 73, crash switches that cut off or isolate all electric equipment are a possibility. Batteries can no longer be regarded as the only power source in crashed airplanes. Although the generators in airplanes powered by reciprocating engines would be stopped during a crash by propeller stoppage, free-running turbines of jet-engine aircraft may necessitate de-energizing fields or short circuiting the generator across its terminals if it would aid in stopping the turbine. Isolation of the electric system can stop electric fuel pumps and close solenoid valves supplying fuel to combustion heaters.

Short-circuit faults in aircraft can probably be protected by rapid acting selective fuses or circuit breakers that would isolate the fault from the rest of the circuit. In general, fuses are less desirable than circuit breakers because of their time-operating characteristics and the fact that they must be replaced after one operation. As indicated by reference 74, the isolating action must be very quick because the circuit voltage drops rapidly in the faulted circuit. This drop in voltage could cripple the entire electric system of the aircraft by allowing relays and contactors to open because of low voltage on the closing coils.

Improved design of the load-carrying cables might result in reduction of the spark-ignition hazard. This improvement might be accomplished by using a conduit containing the electric leads embedded in a solid insulating material. Another possibility in the design of the electric circuits is the inclusion of mechanically weak spots surrounded by inert materials such as powders. During crashes, cable separation would occur at the weak points with the energy released by any sparks being dissipated in inert atmospheres.

IGNITION BY FLAMES OR HOT GASES

Exposure of inflammable vapors to flames or hot gases constitutes the third important fire hazard in aircraft environments. Large, disastrous fires may result from the exposure of inflammable mixtures to exhaust flames and gases or flames initiated by electric spark or heated surface-ignition sources. Possible reduction of these ignition hazards seems more difficult than the reduction of spark or heated surface hazards. Use of the cooled exhaust gases to inert engine nacelles and fuel-tank compartments would prevent contact between inflammable mixtures and hot exhaust gases or flames during flight or ground operation. Simultaneously, the exhaust gases would be inerting hazardous portions of the plane. During a crash, however, such inerting may be ineffective. A possible solution to the problem of flames or hot gases during crashes may be quick acting, crash-actuated mechanisms capable of flooding the engine and exhaust system with fire extinguishing agents.

CONCLUSIONS

An analysis of the available literature included in the survey resulted in the following conclusions:

The inflammability ranges of most hydrocarbon-air mixtures decreased with decreasing mixture pressures and temperatures. The minimum spark-ignition energies of inflammable mixtures and the quenching distances of electrode configurations both increased with decreasing mixture pressures. As a result of these effects, sea-level pressures and temperatures of inflammable mixtures were the most critical design considerations, relative to the reduction of fire hazards in aircraft environments.

Generally, the ignition temperatures of hydrocarbons in air increased with different variables as shown in the following table:

Decreasing variable	Increasing variable
Ignition lag	Mixture turbulence
Igniting surface area	Mixture velocity
Fuel quality or cetane number	Surface catalytic activity
Boiling point or number of carbon atoms in *n*-paraffins	Tetraethyl lead additions

Ignition temperatures of hydrocarbons were also increased if scale or ash existed on the igniting surfaces or if the inflammables were dropped on heated surfaces in the open air. The ignition temperatures of hydrocarbons containing the same number of carbon atoms were lowest for normal paraffins followed by paraffinic isomers and aromatics.

Gasoline exhibited zones of ignition and nonignition for certain oxygen-fuel ratios much in the same manner as normal octane. The ignition temperature of gasoline in air depends on the degree of confinement of the mixture by the experimental apparatus. Dependent on the experimental conditions and the degree of confinement, the ignition temperatures of gasoline in air may range from 450° to 1325° F. The lower and upper limits of inflammability of 100-octane gasoline in air at atmospheric conditions were approximately 1.40 percent and 7.40 percent by volume, respectively, and the minimum ignition pressure was approximately 35 millimeters of mercury absolute. The minimum diameter of a hole or tube through which a gasoline-air mixture flame would not propagate downwards was approximately 0.13 inch as determined from interpolation of data of known mixtures.

Minimum spark-ignition energies of inflammable mixtures were greatly dependent upon the electrode configurations; these energies increased with increasing size of electrodes and mixture velocity and decreased with increasing electrode spacings. Minimum spark-ignition energies as low as 0.28 millijoule were capable of ignition of methane-air mixtures. Electrode material had no visible effect on mixture ignition by capacitance sparks, but the minimum ignition energies of inductance sparks decreased with decreasing electrode-material density. The measured minimum ignition energies of inductance sparks decreased with increasing spark potentials, and were unaffected by alternating or direct currents. Although high humidity content of the air tends to prevent accumulations of electrostatic charges capable of producing sparks having sufficient energy to ignite vapor-air mixtures, practically any transfer of fuel in any environment was hazardous unless the equipment was suitably grounded.

An increase in the amount of diluent gases in a mixture increased the ignition temperature. In hydrocarbon–oxygen–diluent-gas mixtures containing either argon, carbon dioxide, helium or nitrogen as the diluent component, lowest values of quenching distances, minimum ignition energies, and minimum ignition pressures were exhibited with inflammable mixtures containing argon as the diluent gas. Highest values of quenching distances and minimum ignition energies were exhibited with inflammable mixtures containing helium as the diluent gas; highest values of minimum ignition pressures were exhibited with inflammable mixtures containing carbon dioxide as the diluent. In order to render any mixture of 100-octane gasoline and air noninflammable, approximately 42.5, 36.0, and 28.7 percent by volume of nitrogen, automobile exhaust gas, or carbon dioxide, respectively, were necessary.

Application of the survey data to the aircraft-fire problem indicated the possibility of reducing aircraft-fire hazards by means of the following remedial measures:

(1) Prevention of contact of fuels or fuel vapors with the hot exhaust surfaces

(2) Release of an extinguishing agent inside of and around the exhaust system if a crash is imminent

(3) Reduction of the temperature of the exhaust duct or gases below the surface-ignition temperature of gasoline and lubricating oil in the event of a crash

(4) Increase of the surface-ignition temperatures of gasoline and lubricating oil

(5) Use of fuels of reduced volatility

(6) Elimination of the electrical generating system as an ignition hazard in the event of a crash

(7) Inerting of engine nacelles and wing compartments.

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TABLE I—SURFACE IGNITION TEMPERATURES OF SEVERAL INFLAMMABLES IN AIR

(a) Ignition surfaces, heated 6-inch-diameter steel tube and open steel plate (reference 72)

Fuel	Ignition temperature (°F)		Flash point (°F)
	Tube [a]	Plate	
Gasoline (unleaded)	473	>1238	−44
100-Octane aviation gasoline (leaded)	734	>1238	−44
Kerosene	417	1202	108
Hydraulic fluid	455	752	302
Lubricating oil	572	806	482

[a] Heated-surface ignition environments.

(b) Ignition surfaces, heated nickel or iron plates (reference 24)

[Plate, 0.5 or 1.0 mm by 45 mm by 140 mm; temperatures measured by iron-constantan thermocouple soldered to plate.]

Fuel	Surface ignition temperature (°F)
Benzene	1400
Toluene	1409
Ethyl alcohol	1274
Cyclohexane	1125
n-Pentane	1085
n-Heptane	1058
n-Decane	1085
Rumanian aviation gasoline	1085
Shale-oil gasoline	1040
Green mineral oil	977
Dimethylcyclohexene	833

TABLE II—EFFECT OF IGNITION-SURFACE COMPOSITION ON SURFACE IGNITION TEMPERATURES OF SEVERAL FUELS IGNITED IN AIR BY STATIC CRUCIBLE METHOD

(a) Data from reference 40

[All configurations are 106-cc cylinders except pyrex surface, which is 125-cc spherical configuration.]

Fuel	Surface ignition temperature (°F)			
	Pyrex	Copper	Low-carbon steel	Chromium
n-Hexane	479	510	516	513
n-Heptane	452	481	484	483
Isobutyl alcohol	825	861	902	862
Gasoline (Socony)	497	534	550	559

(b) Data from reference 36

[Ignition volume, 1180 cc; ignition lag, 1 sec.]

Fuel	Surface ignition temperature (°F)	
	Platinum	Pyrex
n-Pentane (technical grade)	1074	1009
n-Hexane	968	959
n-Octane	856	815
Isooctane	1042	999
Isododecane	993	930
Benzene	1213	1144
Toluene	1171	1119
Mesitylene	1150	1110
p-Xylene	1144	1103
Methyl alcohol	1065	997
Ethyl alcohol (abs.)	1035	1011
n-Propyl alcohol	1004	979
Benzyl alcohol	936	829
Isopropyl alcohol	1148	990
Isobutyl alcohol	1008	972
Isoamyl alcohol	964	840
Ethylene glycol	972	855

TABLE III—EFFECT OF OCTANE NUMBER ON SURFACE IGNITION TEMPERATURE OF UNLEADED LIQUID FUELS IGNITED IN AIR BY DYNAMIC CRUCIBLE METHOD OF IGNITION (REFERENCE 78)

Fuel	Octane number	Surface ignition temperature (°F) [a]	Flash point (°F)	A.S.T.M. distillation (°F)				Reid vapor pressure (lb at 100° F)
				Initial boiling point	Percentage evaporated			
					10	50	90	
Certified 2,2,4-trimethylpentane	100	970		211	211	211	211	1.5
Paraffinic safety fuel	99	930	110	330	340	342	344	about 0.1
Straight-run gasoline plus isooctane plus isopentane (commercial blend)	85	910			158 max.	212 max.	257 max.	7.0 max.
Diisobutylene (mixture of 2 isomers)	[b] 84 to 100+	880		220				
Aromatic safety fuel	75	790	110	327	338	354	381	about 0.1
Straight-run aviation gasoline	74	830			158 max.	212 max.	257 max.	7.0 max.
Certified *n*-heptane	0	490 to 530 [c] 790		209	209	209	209	1.6

[a] Air-flow rate, 50 cc/min at atmospheric pressure and temperature; fuel addition, 0.01 ml from pipette at 2-minute intervals; ignition surface, stainless steel.
[b] Depends on knock test method.
[c] Nonignition zone from 540 to 760° F.

TABLE IV—EFFECT OF ADDITION OF TETRAETHYL LEAD ON SURFACE IGNITION TEMPERATURE OF SEVERAL FUELS AS DETERMINED BY DYNAMIC CRUCIBLE METHOD

(a) Data from references 79 and 17

Fuel	Ignition temperature without TEL (°F)	Ignition temperature increase with TEL (°F)	Reference
Pentane	959	[a] 135	79
Isohexane	977	[a] 83	79
Heptane	806	[a] 149	79
Gasoline (Shell)	860	[a] 148	79
Benzene	1274	[a] 32	79
Cyclohexane	995	[a] 49	79
Methylcyclohexane	878	[a] 166	79
Cetane	450	[b] 482	17
n-Heptane	498	[b] 341	17
Isooctane	985	[b] 92	17
Isododecane	932	[b] 63	17

[a] 0.25 percent by volume TEL added (approximately 9.5 cc/gal). (Air-flow rate, 330 cc/min; fuel drop size, 0.012–0.013 cc); ignition surface, iron.
[b] 3 cc/gal TEL added. (Air-flow rate, 54 cc/min; fuel drop size, 8 mg); ignition surface, stainless steel.

(b) Surface ignition temperatures obtained from reference 78

Fuel	Ignition temperature without TEL (°F) [a]	Ignition temperature increase with TEL (°F) [a]	Flash point (°F)	A. S. T. M. distillation (°F)				Reid vapor pressure (lb at 100° F)
				Initial boiling point	Percentage evaporated			
					10	50	90	
Certified *n*-heptane	490–530			209	209	209	209	1.6
	[b] 790	40						
Certified 2,2,4-trimethylpentane	970	90		211	211	211	211	1.5
Paraffinic safety fuel	930	60	110	330	340	342	344	about 0.1
Aromatic safety fuel	790	90	110	327	338	354	381	about 0.1
Straight-run aviation gasoline	830	40			158 max.	212 max.	257 max.	7.0 max.
Straight-run gasoline plus isooctane plus isopentane (commercial blend)	910	50			158 max.	212 max.	257 max.	7.0 max.

[a] Air-flow rate, 50 cc/min at atmospheric pressure and temperature; fuel addition, 0.01 ml from pipette at 2-minute intervals; ignition surface, stainless steel; 3 cc/gal TEL added.
[b] Nonignition zone from 540 to 760° F.

TABLE V—IGNITION TEMPERATURES OF VARIOUS FUELS AND OILS

[All results from experiments conducted at atmospheric pressure and temperature unless otherwise noted.]

Fuel	Fuel specification	Reference	Ignition method	Ignition atmosphere	Igniting surface	Ignition lag (sec)	Ignition temperature (°F)
Gasoline	Socony	40	[a]	Air	Pyrex		[b] 508
Aviation gasoline	62.0° A. P. I.; initial boiling point, 111° F	80	[a]	Air	Pyrex	50	532
Gasoline	Socony	40	[a]	Air	Copper		[c] 534
Gasoline	Socony	40	[a]	Air	Low carbon steel		[c] 550
Aviation gasoline	63.6° A. P. I.; boiling range, 111°–324° F	80	[a]	Air	Pyrex	6	554
Gasoline	Socony	40	[a]	Air	Chromium		[c] 559
Aviation gasoline		80	[a]	Air	Pyrex	13	563
Gasoline	66.8° A. P. I.; unleaded; 73 octane	61, 81	[a]	Air	Pyrex		570
Aviation gasoline	63.8° A. P. I.; boiling range, 109°–327° F	80	[a]	Air	Pyrex	6–7	590
Aviation gasoline	63.8° A. P. I.; boiling range, 106°–325° F	80	[a]	Air	Pyrex	8	594
Aviation gasoline	63.9° A. P. I.; boiling range, 135°–325° F	80	[a]	Air	Pyrex		624
Aviation gasoline	63.8° A. P. I.; boiling range, 109°–327° F	80	[a]	Air	Pyrex	4–5	640
Gasoline	68.9° A. P. I.; unleaded; 92 octane	61, 81	[a]	Air	Pyrex		734
Gasoline	66.1° A. P. I.; unleaded; 100 octane	61, 81	[a]	Air	Pyrex		804
Gasoline	Mean boiling point, 167° F	82	[d]	Oxygen	Steel		545
Safety fuel	Unleaded; 75 octane; aromatic	39	[d]	Air			790
Safety fuel	Unleaded; 99 octane; paraffinic	39	[d]	Air			930
Aviation gasoline	Leaded; 100 octane	39	[d]	Air			960
Aviation gasoline	Straight run	78	[d]	Air	Steel	<60	830
Gasoline		83		Air		3	626
Gasoline		16	[e]	Air	Pyrex		865
Gasoline	Unleaded; flash point, −44° F	72	[f]	Air	Steel		473
Aviation gasoline		12	[f]	Air	Steel	7	599
Aviation gasoline	Leaded; 100 octane; flash point, −44° F	72	[f]	Air	Steel		734
Gasoline		25	[g]	Air	Copper		1004
Gasoline	From shale oil	24	[g]	Air	Iron or nickel		1040
Aviation gasoline	Rumanian	24	[g]	Air	Iron or nickel		1085
Gasoline	Unleaded; flash point, −44° F	72	[g]	Air	Steel		>1238
Aviation gasoline	Leaded; 100 octane; flash point, −44° F	72	[g]	Air	Steel		>1238
Gasoline		25	[g]	Air	Iron		1328
Gasoline	Boiling range, 100°–400° F; flash point, −50° to −45° F; specific gravity, 0.75	37, 84					495
Gasoline		38		Oxygen			536
Gasoline		85		Air			608
Gasoline	Shell	79	[d]	Air	Iron		860
Kerosene	Water white	39	[d]	Air			520
Kerosene	Flash point, 108° F	72	[f]	Air	Steel		417
Kerosene	Flash point, 108° F	72	[g]	Air	Steel		1202
Kerosene	Flash point, 100°–165° F	37, 84					490
Aircraft lubricating oil	SAE 60, mid-continent solvent extracted	39	[d]	Air			750
Lubricating oil	Flash point, >500° F	78	[d]	Air	Steel	<60	750
Lubricating oil	Flash point, 482° F	72	[f]	Air	Steel		572
Lubricating oil	Flash point, 482° F	72	[g]	Air	Steel		806
Naval lubricating oil	N. S. 2135	86	[h]	Air	Pyrex		685
Turbine lubricating oil	Open-cup flash point, 400° F	84					700

[a] Static crucible method.
[b] Average of five trials.
[c] Lowest temperature measured.
[d] Dynamic crucible method.
[e] Dynamic heated-tube method.
[f] Liquid dropped into heated iron or steel tube (static).
[g] Liquid dropped on heated metal plate.
[h] ASTM D286–30.

TABLE VI—LIMITS OF INFLAMMABILITY OF GASOLINES AND KEROSENE IN AIR

[All results are from investigations conducted at atmospheric pressure and temperature unless otherwise noted.]

Fuel	Specification	Reference	Ignition source	Ignition environment	Lower limit [a]	Upper limit [a]
Gasoline		87	Spark or flame	Vertical tube	1.40	6.90
Gasoline	Specific gravity, 0.75; closed-cup flash point, −50° to −45° F	37, 84			1.3	6.0
Gasoline	Unleaded; 100 octane; 66.1° A. P. I.; RVP, 3.25 lb/sq in. at 77° F	61	Alcohol flame	Vertical tube	1.45	7.40
Gasoline	Unleaded; 92 octane; 68.9° A. P. I.; RVP, 3.52 lb/sq in. at 77° F	61	Alcohol flame	Vertical tube	1.50	7.60
Gasoline	Unleaded; 73 octane; 66.8° A. P. I.; RVP, 3.87 lb/sq in. at 77° F	61	Alcohol flame	Vertical tube	1.50	7.60
Kerosene	Closed-cup flash point, 100°–165° F	37, 84	Alcohol flame	Vertical tube	1.50	7.60
					1.16	6.0

[a] Inflammability limits are volumetric percentages of fuel in fuel-air mixture.

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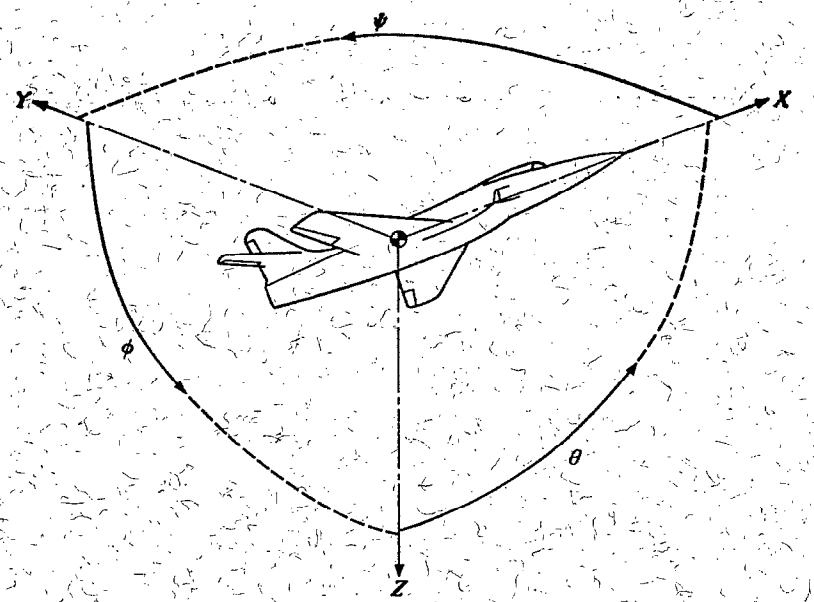

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph

1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft